

A COMPARATIVE ANALYSIS OF SMALL ADVANCED NAVAL VEHICLES AND DISPLACEMENT-HULL NAVAL SHIP DESIGN

by

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partial fulfillment of the requirements for the degrees of Ocean Engineer and
Master of Science in Ocean Systems Management.

Abstract

A small naval ship, derives its desirability as a naval vessel, due to the fact that it is an inexpensive solution to the problem of maritime defense. This thesis compares five of these naval vessels, two displacement-hull form, two hydrofoils, and one Surface Effect Ship. The procedure of the comparative analysis begins with a comparison of the gross characteristics of the ships, and uses several design indices to examine the factors that influenced each design. Differences in design criteria, standards, and practices are identified and assessed, and the advantages and disadvantages of each design are presented.

Thesis Supervisor: Professor Paul. E. Sullivan
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-

Αφιερώνεται στον πατέρα μου, και στην μνήμη της
μητέρας μου.

Dedicated to my father, and to the memory of my
mother.

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CHAPTER 1

INTRODUCTION

1.1 Purpose of the study

Traditionally, attention has been focused on requirements and developments of large ships. In the last twenty years, however, significant changes have occurred in the development and use of fast patrol boats. The famed PT and E boats of World War II spawned a second generation of missile-armed boats that emerged in the late 1950's and 1960's and have generally been referred to as Fast Patrol Boats (FPBs).

This thesis studies and compares some of the latest versions of FPBs. The ships of the study represent each hull technology currently used for FPBs. The differences in design and construction between two conventional (displacement), two hydrofoil and one SES ship design are presented. The differences in the ships are analyzed as they are presently constructed, and the differences in the design criteria and standards (evidenced as differences in design indices) are tabulated by functional area to allow a side-by-side comparison.

1.2 Rationale for ship selection

The comparative analysis of this study is focused to a full load displacement range of 70 to 250 tons. The basic idea is to cover three different small naval ship designs: one "conventional", and two different "high performance"

(hydrofoil and SES) designs. For every design, one ship of about 100 tons full load displacement is evaluated. In the area of 230 tons full load weight one hydrofoil and one "conventional" vessel are examined.

The method chosen to categorize the vessels, is that of the identification of the supporting force or sustention.

There are three different types of sustention:

Unpowered Static Lift

Powered Dynamic Lift

Powered Static Lift.

All the vessels of the study operate by one of these three forms of supporting force or some combination of these forms. (See figure 1.1). Unpowered static lift is a characteristic of large displacement type ships. Hydrofoils operate with powered dynamic lift, and SESs are an example of the powered static lift type of vessels. Planing craft generate dynamic lift forces at high speeds, as they enter the planing regime. Finally, high-speed displacement vessels could be placed in the unpowered static lift-planing region.

First, the two hydrofoils were selected. The hydrofoil menu was limited due to the small amount of hydrofoil types in the naval market today, as well as the restrictions imposed by the unavailability of classified or proprietary information. PHM (U.S.A), and M161 (Israel) were selected, covering the range of 70 to 250 tons. For conventional hull types, CPIC (U.S.A for South Korea), and SPICA II (Sweden) were picked in order to allow a comparison with M161 and PHM, correspondingly. For the

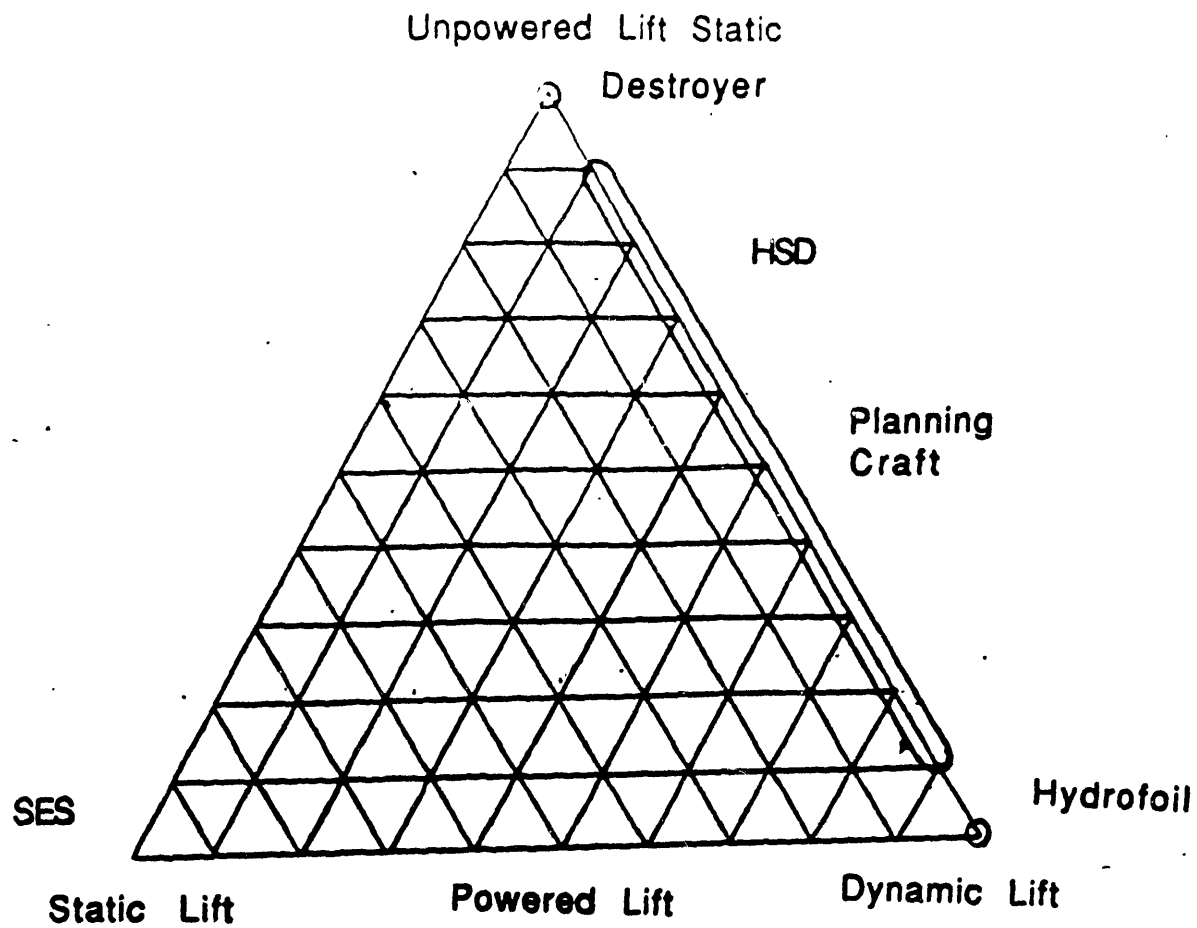


Fig. 1.1 Sustention triangle (Source: Jewel D., "Hybrid Fluid-Media Vehicles", Naval ship research and development center, Aug. 73).

SES design, APB34 (a Bell Halter design) was chosen, at the same full load displacement as M161. For this study, U.S. and foreign constructors were selected in order to give a flavor of the differences in the design philosophy of small combatants of U.S. and foreign navies.

1.3 Study approach

At first, a comparison of the gross description of the five different ships is made. Later an analysis of the weight and volume utilization is made. As a derivative of the weight and volume analysis, a collection of specific parameters (design indices) is developed. The design indices are ratios of volume and weight or other characteristics such as crew size or shaft horsepower, or combinations of the above. These specific parameters give a quantitative measure of the ships' characteristics, design criteria, as well as ship performance. The design indices used in this study can be found in Appendix C. Although the analysis occupies three different ship types, many common characteristics are realized, and these are presented as trends by mission or by size.

Finally, producibility aspects of the planing and high speed displacement hull, hydrofoil and SES ship design are presented.

1.4 Sources for the study

The design indices for each type of ship are derived using the information presented in the bibliography. Unfortunately, there was no response from the shipbuilders

(requested to provide more details about every ship) due to problems with proprietary information.

Reference 24 provided most of the design indices for the conventional hull vessels and PHM. The Advanced Surface Ship Evaluation Tool (ASSET) for hydrofoil design was used to obtain the indices for the two hydrofoils. The design characteristics of PHM and M161 were used as input, and two "new" designs were derived. The accuracy of the results obtained from ASSET was verified, after comparing them with the information found in the corresponding bibliography .

For the SES design, reference 44 was used. Many of the design indices were provided from the SES design group of Naval Sea Systems Command. The information from NAVSEA was not focused on APB34 design, but on the design of a similar naval vessel, of the same role, displacement, payload, maximum and endurance speed, and range. The design indices of APB34 contain a larger amount of error, compared to the design indices of the other vessels, as they represent a design, and not a tested fighting ship having years of service at sea.

Volumes and areas for all the vessels were measured by the writer from the corresponding drawings, or taken from the papers in the bibliography, or derived by ASSET. The deck space areas of the vessels presented in chapter 4 were measured by the writer.

CHAPTER 2

HISTORY OF SMALL COMBATANTS

Since their introduction in the 1950's, fast patrol boats have become an increasingly important part of the world's navies. Many nations have found them an attractive alternative to surface combatants due to their lower cost and efficient use of manpower and budget. Countries are becoming increasingly aware of the capability of this type of vessel, and the need for such a capability in order to meet the pressure exerted on the modern navy operating in the regional or even global environment.

The missions that a modern navy is required to meet have expanded greatly, both in number and complexity. Historically, most nations have required coastal patrol within a limited perimeter, typically 3 to 12 miles. The advent of the 200-mile limit has expanded this area to a point where only comparatively large numbers of high-speed vessels equipped with the most sophisticated electronics and weapons are able to cover it adequately. Since destroyers, frigates, and even corvettes are far too costly to be acquired in sufficient quantity to meet this challenge, the fast patrol/attack craft has been adopted by many navies.

In some navies, fast patrol craft often constitute the entire sea-denial force, with the occasional exception of a few corvettes. Some nations have developed extremely effective navies based entirely on FPBs which have provided graphic evidence of the validity of the FPB concept, even against much larger displacement vessels.

Perhaps the most persuasive evidence of the success of fast patrol/attack craft is the sheer magnitude of their distribution. There are over 2000 FPBs in service around the world, and several hundred more are on order.

As the FPBs were evolving, the electronics and weapons systems associated with them have progressed rapidly as well. There are increasing numbers of high performance advanced weapons systems specifically designed for installation on FPB hulls. Surface-to-surface missiles, introduced on FPBs by the Soviet Union in 1959, have proven their effectiveness several times over. Rapid rate-of-fire guns are mandatory for anti-aircraft and anti-missile defense, in addition to their roles as anti-surface and aiding force support. Sophisticated electronics and fire control systems are necessary to handle all of these equipments, and they are even more complex as the available reaction time drops.

2.1 The Planing hull form and HSD vessels

Since the early 1900s there has been little change in the basic underwater-hull forms used in the design of fast Naval vessels, although there has been notable improvement in hull lines. Thus there is remarkably little difference in either hull form or performance between the Turbinia, Sir Charles Parsons' forerunner of the Steam-turbine-powered ship, which made 36 kt in 1896 and contemporary Fast Attack Crafts (FACs) with round-bilge hulls. Typical round-bilge hull forms, and classical planing hull forms are presented in figures 2.1 and 2.2.

Although the the fast attack craft is limited in many respects by its small size compared with corvettes and

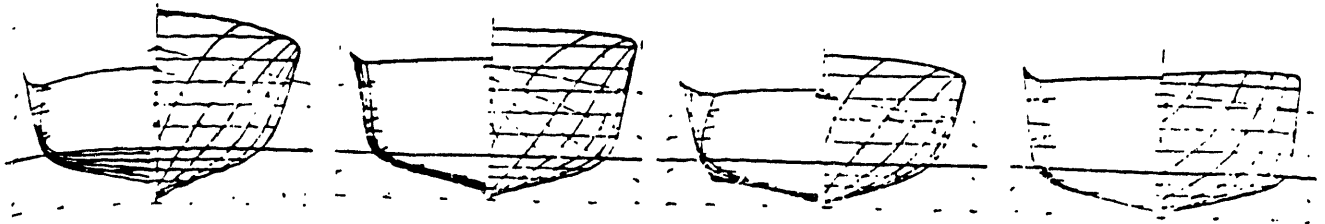


Fig. 2.1 Typical modern round bilge hull forms (Source: Sornin E. H., "FAC hull forms a comparative study of two different concepts", International Defence review, Jul 81).

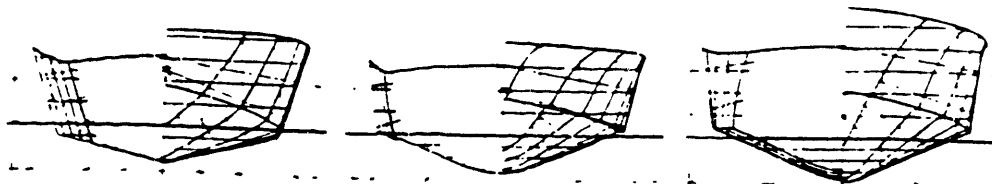


Fig. 2.2 Typical deep-Vee hull forms (Source: Sornin E. H., "FAC hull forms a comparative study of two different concepts", International Defence review, Jul 81).

frigates, the cost effectiveness of this type of weapon platform is leading to its procurement in increasing numbers, and to a profusion of new designs in the market.

2.2 The Hydrofoils

A United States patent for a hydrofoil was filed in the late 1880s, about the same time as the early airplane and airfoil patents. The earliest record of a successful hydrofoil flight is 1894 at Chicago, Illinois. The early attempts to exploit the hydrofoil concept were frustrated by the lack of suitable structural materials and power plants. Advancement in these areas has permitted the development, over the past 30-40 years, of the technology necessary to achieve reliable and effective hydrofoil ships for military operations.

In recent years, many countries have demonstrated an interest in applying hydrofoils to military missions. Italy has been developing its class of fully submerged hydrofoils since the early 1970s. Israel contracted for its first hydrofoil in 1977. Hydrofoils are under construction in Indonesia. The Soviet Union leads the world with active hydrofoil development from the end of World War II. Today the USSR has the largest number of hydrofoils, military and civilian in the world.

2.3 The SESs

The technology of SES and its close relative, the hovercraft, has been under development for approximately 30 years. Experimental prototypes have been built in Britain and the U.S. in the late 1950's and early 1960's.

Operationally useful craft from 5 to 200 tons have been applied to both commercial and military missions since the middle to late 1960's.

The more efficient SES was initially developed in the United States and Britain in the early 1960's. In the United States a joint program was initiated by the Maritime Administration, which funded the construction of two 100-ton SES test craft during 1969-71. These craft, the SES 100-A built by Aerojet General Corporation and the SES-100B built by Bell Aerospace Textron, underwent extensive testing and operational evaluation through 1977. Later SES designs include the SES 200, the Model 522A Coast Guard SES (delivered in 1982), and the Model 511A Fast Patrol Craft.

CHAPTER 3

GROSS SHIP DESCRIPTION

This chapter is comprised of a brief description of each ship included in the study, in order to familiarize the reader with the ships.

In figures 3.1 through 3.5 the gross characteristics of each ship are presented, in addition to the country for which they were constructed and their delivery period.

Figure 3.6 presents the ships as they could appear in dry dock next to each other in a scale ratio of 1/400, in order for the reader to gain an idea of their appearance and their relative size.

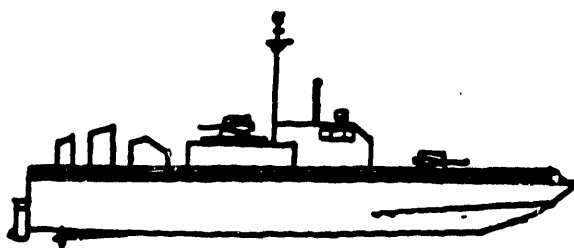


Figure 3.1

CPIC

Country: USA(for South Korea)**Builder:** Tacoma**Year delivered:** 1977**L.O.A.:** 99.9 FT**Displacement:** 72.5 Tons F.L.**Speed:** 45 Knots**Complement:** 11

Propulsion: (3) AVCO-LYCOMING Gas Turbines at 6000 SHP
V-Drive and 3 CRP Propellers.
(2) Volvo Diesel Outdrives.

Weapons: (1) Twin Emerlec 30 mm
(2) Twin M60 Machine Guns
(2) 40 mm Grenade Launchers

Sensors: MK 93 G Fire Control System.

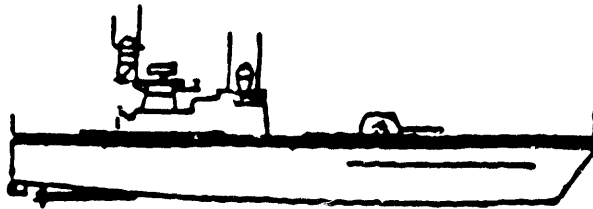


Figure 3.2

SPICA II CLASS**Country:** Sweden**Builder:** Karlskrona**Year delivered:** 1973-1976**L.O.A.:** 143 FT**Displacement:** 229 Tons F.L**Speed:** 40.5 Knots**Complement:** 27

Propulsion: (3) Rolls Royce Proteus Gas Turbines at 12900 SHP
 (3) Shafts with V-Drive and Fully-Cavitating
 CPR Propellers.

Weapons: (8) RBS 15 SSM (Single launchers)
 (1) 57 mm L70 MK2 Boffors
 (6) 21-Inch Torpedo tubes
 Mine Rails
 (4) A/S Elma Grenade launchers (in some)

Sensors: Phillips 9LV 200 MK2 Fire Control System.

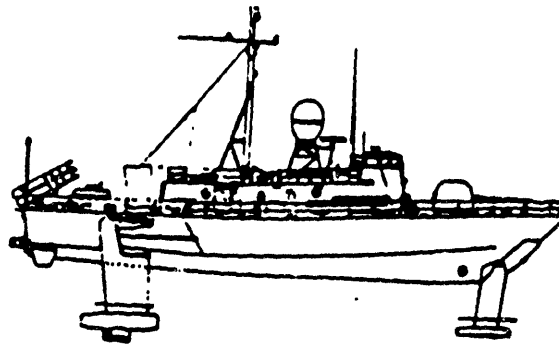


Figure 3.3

PHM CLASS Hydrofoil

Country: USA

Builder: Boeing Aerospace

Year delivered: 1977-82

L.O.A.: 132 FT

Displacement: 241 Tons F.L.

Speed: 50 + Knots

Complement: 21-24

Propulsion: Foilborne: (1) LM 2500 at 17000 SHP
 Driving a single foilborne propulsion pump.
 Hullborne: (2) Mercedes-Benz Diesels at 1600 SHP
 Driving twin Aerojet pumps.

Weapons: (8) Harpoon SSM
 (1) OTO MELARA 76mm gun.
 Can be delivered with (2) MK20 RH 202 20mm
 Secondary guns.

Sensors: WM-28 Weapons Control or Mk 92 (Mod I)

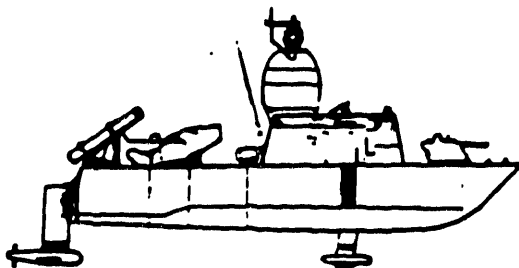


Figure 3.4

M 161 CLASS Hydrofoil**Country:** Israel**Builder:** Israel Shipyards**Year delivered:** 1983-85**L.O.A.:** 84 FT**Displacement:** 105 Tons F.L.**Speed:** 52 Knots**Complement:** 3 min-15 max

Propulsion: Foilborne: (1) Allison 501-KF at 5400 SHP
 Z-Drive with supercavitating four bladed CCP
 Hullborne: Twin Maritime Industries
 retractable and steerable outdrives at 130 HP.
 Three bladed FP steel propellers.

Weapons: (4) Harpoon SSM
 (2) IAI Gabriel MK III SSM
 (1) Twin Emerlec 30 mm

Sensors: ECCM/ESM Fire Control Radar.

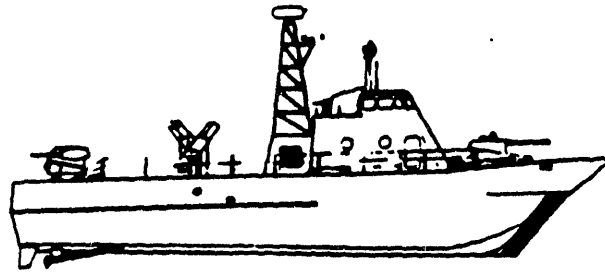


Figure 3.5 APB 34 CLASS SES

Country: USA

Builder: Bell Halter

Year delivered: Design

L.O.A.: 111.5 FT

Displacement: 118 Tons F.L.

Speed: 45 Knots

Complement: 24

Propulsion: (2) MTU Diesels at 5500 SHP

Weapons: (4) Exocet MK 39 SSM
 (1) Bofors 40 mm gun
 (2) Emerlec 30 mm twin guns
 (2) 50 Cal machine guns.

Sensors: Phillips 9LV 200 MK2 Fire Control System.

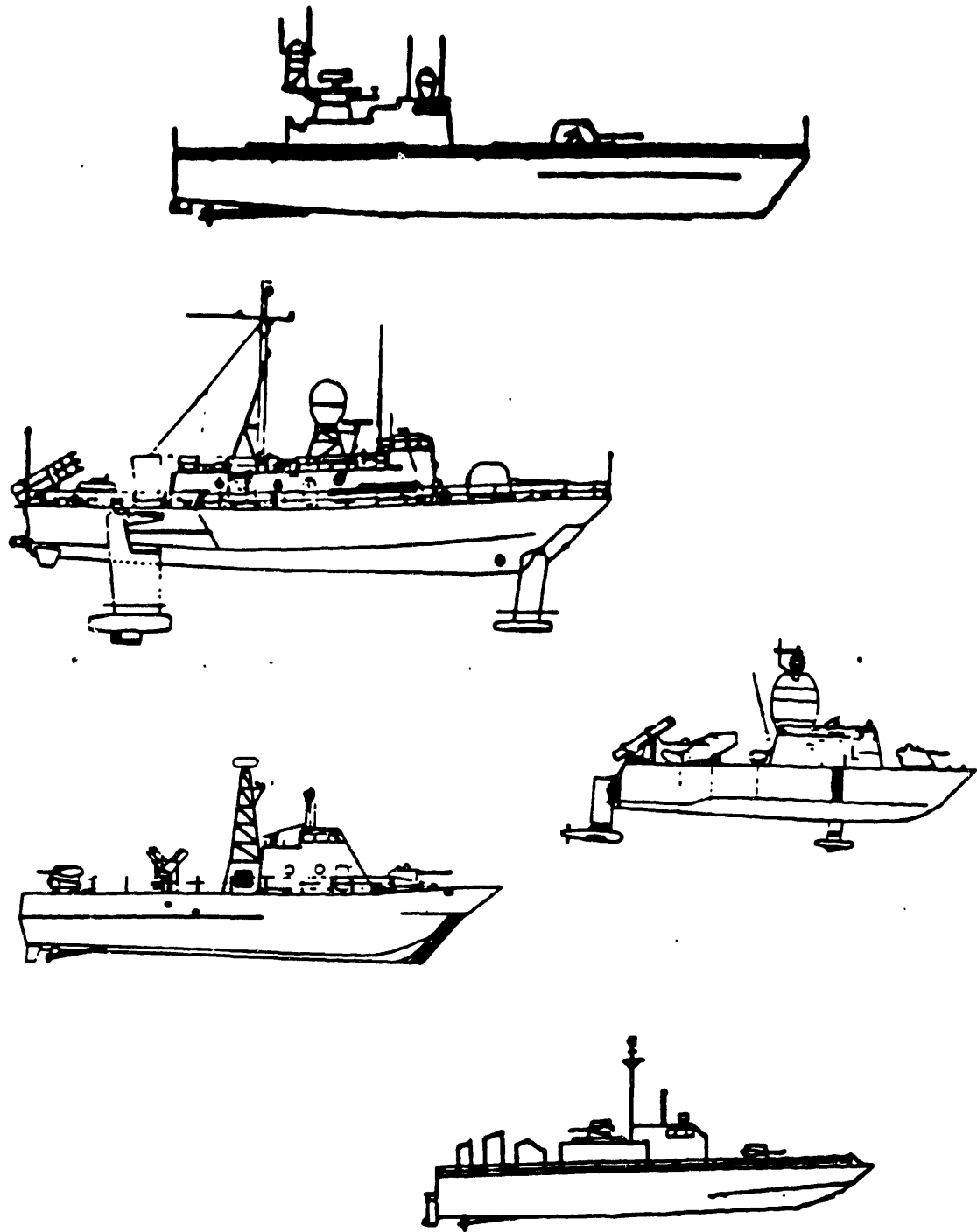


Fig. 3.6 Size Comparison

CHAPTER 4

OVERALL ANALYSIS OF SHIPS

This chapter compares the overall design features of the ships. In order to start analyzing the ships, the design differences in full load weights, weight, volume, and deck space allocation fractions, as well as, the overall design characteristics should be examined on a gross level. Further in depth analysis of the results of this chapter will be presented in following chapters.

4.1 GROSS CHARACTERISTICS

The major characteristics of the vessels are shown in table 4.1. The first two vessels are of the monohull design (the CPIC and the SPICA II). After the monohulls the two hydrofoils, PHM and M161 are presented. The final vessel is the SES design (APB34). The ships' payload is presented in table 4.2.

4.1.1 The CPIC

This short ship, built by Tacoma shipyards for the South Korean Navy in 1977 is a short range, high speed patrol craft designed for coastal missions. Its sophisticated all-gun armament, shallow draft, and high speed make CPIC ideally suited for "guerrilla" warfare operations, insertion, and small patrol boat actions.

TABLE 4.1

SHIP	CPIC	SPICA II	PHM	M161	APB34
L.O.A (ft)	99.9	143	132	84	111.5
Beam (ft)	18.3	7.1	29.0	24.0	39.0
Draft (ft)	6.1	7.9	6.2/23.2/8.2*	4.8/15.8/5.6*	4.6
ΔFL (Tons)	72.5	229	241	105	118
Volume (ft ³)	11720	29127	36450	16475	23572
V _{Max} (KT)	45	40.5	50+	52	45
Range (NM)	500(16)	1500(16)	1000(14)	750-1150(42)	1400(18)
SHIP _{Boost}	6000	12900	17000	5400	5500
Plant	COGOG	GT	COGOG	COGOG	Diesel
Accommodations	11	32	23	4-15	24
Stores (Day)	2.5	n/a	5	1	1
Year	77	73-76	77-82	83-85	Design

Hullborne retracted/hullborne extended/foilborne.

TABLE 4.2

PAYLOAD

SHIP	CPIC	SPICA II	PHM	M161	APB34
Missiles	None	(8) RBS 15	(8) Harpoon	(4) Harpoon (2) Gabriel	(4) Exoset (2) RBOC
Torpedoes	None	(6) 21 in	None	None	None
Guns	Twin 30 mm (4) 50 cal	(1) 57 mm	(1) 76 mm	Twin 30 mm	(1) 40mm (2) 30 mm (4) 50 cal

4.1.2 The SPICA II

This is a Swedish ship built by Karlskrona Varnet between 1973-76. The SPICA II differs in appearance from other ships of the similar type, as it has a small deckhouse set far aft. The ships of this design underwent major modifications in 1984. SSM missile launchers were fitted with new CIC modernized electronics and a new 57mm gun and hull mounted sonar. These ships have been built and then modernized for surface and underwater surveillance in the restricted waters around Scandinavia.

4.1.3 The PHM

The NATO Fast Patrol Ship Guided missile (NATO/ PHM) originated in mid-1969 to combat the threat posed by missile-armed Soviet Osa/Komar type fast patrol boats in the Mediterranean waters. The first PHM, Pegasus, completed its acceptance trials on June 1977. Five other ships of this design were built by Boeing Marine Systems, up to 1982.

The PHM has sufficient design flexibility to allow for individual combat systems variations by any country. Thus it can be adapted for such roles as antisubmarine warfare, fisheries law enforcement, and protection of offshore resources. In this study the design now active in the U.S. navy will be presented. PHM is capable of crossing oceans with fast carrier task groups, convoys of merchant ships and amphibious assault groups, with the aid of an at-sea refuelling

4.1.4 The M161

The first M161, Shimrit, designed by Grumman Aerospace Corporation, was launched in Florida in 1981. Two more M161s have been built by Israel Shipyards, Limited, in later years.

The M161 is a very powerfully-armed strike vessel. Its operation as a "day-boat" has had a significant influence on the choice of the ship's systems and arrangements. The M161 has been designed for a wide range of military roles, and can be fitted with a variety of weapons. Designs are available with differing payloads and endurances for applications including gunboat, troop transport, surveillance craft, missile boat, inshore ASW patrol, EEZ patrol and search and rescue.

4.1.5 The APB34

APB34 is a design created by Bell-Halter, a joint venture of Bell Aerospace Textron and Halter Marine services, Inc.

APB34 design represents an improvement over the successful SES-100B design.

APB34 offers a greater speed for a given horsepower, with better seakeeping and platform stability, particularly in high sea states. Its greater deck area enables awesome concentration of fire power capability, provided that the designer can fit them weight-wise.

4.2 COMPARISON BY WEIGHTS

In order to be able to categorize all weight indices the navy weight classification system Ships Work Breakdown Structure (SWBS) is used (See Appendix A). Further information about this system may be found in reference 21. The weight allocation fraction for each ship can be seen in figure 4.1 The weight breakdown for each ship in absolute scale can be found in figure 4.2.

4.2.1 Weight allocation fraction

4.2.1.1 SWBS Group 100 (Hull structures)

The advantage of the Aluminum construction can be easily seen, comparing the hull structure fraction. SPICA II, an all Steel vessel, has 36 % of its overall weight dedicated to structure, leaving less weight fraction for other areas. The same advantage exists for the hydrofoils, although their hull must have additional strength to resist wave impact and emergency landing in high seas at foilborne speeds. The advantage of the Aluminum hull cannot be seen in APB34 as the safety factors used in SES structural designs are larger than those of the monohulls. The SES design of our study needed large safety factors in order to provide a reasonable margin to account for unknowns in the design process, due to the limited experience from the SESs that are already at sea.

4.2.1.2 SWBS Group 200 (Propulsion plant)

The incorporation of the diesels for hullborne propulsion drives the weight group 200 fraction of the PHM

up. The three gas turbines and the V-drive of the CPIC have the same effect as above, although they make the small CPIC a very fast craft.

4.2.1.3 SWBS Group 300 (Electric plant)

The group 300 weight fraction is a direct consequence of the payload each ship can carry. The M161 an extremely powerful vessel, has the biggest fraction as it is carrying two big generators to fulfill its payload requirements. The minimal discrete generator size of the CPIC, results in a comparatively high electric plant weight fraction.

4.2.1.4 SWBS Group 400 (Command and Surveillance)

M161 with a large radome on the deckhouse has the highest group 400 weight fraction. SPICA II comes next, having undergone major modifications lately; as Europeans tend to emphasize command and surveillance more than the U.S. designers. Excluding the CPIC, the other two American designs have the similar group 400 weight fraction.

4.2.1.5 SWBS Group 500 (Auxiliary systems)

The two hydrofoils have the higher group 500 weight fraction, as they need very powerful hydraulic systems for the demands of their control systems, in both hullborne and foilborne operation. The multiple levels of redundancy needed to assure continued operation in the event of system failure, drive the auxiliary systems weight up.

The M161 has a lower group 500 fraction than that of the PHM as it has to support a much smaller crew. Lifting fans are the major contributors to the increase of the auxiliary systems weight fraction in the APB34. SPICA II much larger than the CPIC, with a lengthier mission, and requirement to support a larger crew, has a larger auxiliary systems weight fraction.

4.2.1.6 SWBS Group 600 (Outfit and furnishings)

CPIC, due to its size and its short mission, and M161, due to its very small area devoted to personnel, as well as, its short mission have the smaller group 600 weight fraction. The M161 fraction is very small, as crew comforts take second place in this ship. The other vessels have approximately the same outfit and furnishings weight fraction, with the more "spacious" European design SPICA II devoting a larger fraction to the group 600 weights.

4.2.1.7 SWBS Group 700 (Armament)

The variation from 3.6% to 15.2% is not a good indicator of combatibility, since volume of weapon systems is more important in some of the ships. But it must be noted that the heavily loaded, for its size M161 has the bigger armament weight fraction

4.2.1.8 Loads and margins fraction

When the Group 100-700 weights are subtracted from full load displacement the remaining weights are the loads and margins.

4.2.2 Absolute Scale Weights

Figure 4.2 presents the distribution of the ship's weights in absolute scale.

The group 100 weight of SPICA II is significantly larger than that of the PHM, although the ships have approximately the same full load weight. The opposite happens to the group 200 weight of the two ships. PHM, due to its large hydraulic system has a much bigger group 500 weight. The weight of the loads carried by PHM is bigger than that of the SPICA II.

Comparing APB34 and M161, vessels which have approximately the same full load displacement, we should mention the group 100 weight of the APB34, for the reasons explained earlier in this chapter.

4.3 VOLUME COMPARISON

The different design philosophies, design trends, and mission characteristics of each ship play a significant role in the allocation of volume around a navy vessel. The internal volume devoted to different ship functions is divided by the Ship Space Classification System (See Appendix B) in four major groups: V1 (Mission support), V2 (Human support), V3 (Ship support), V4 (Ship mobility

systems). The internal volume allocation for each vessel can be found in figure 4.3.

There is always a problem with error when comparing volumes. If even one excludes the accuracy of measurement, volume measurements are still subject to errors, due to the overlay of the functional areas in a ship.

4.3.1 Mission support (V1)

Mission area is driven by the mission and combat systems weight fraction. The larger the mission support fraction the more significant the mission impact is on the ship.

For weapons systems with the same density, the mission support fraction and the payload weight fraction must be alike. M161 has the largest V1 fraction, due to its austerity for living spaces. APB34 has a smaller V1 fraction but a high payload weight fraction. This means that her weapons are denser.

4.3.2 Personnel Support (V2)

Personnel support is driven by human support and manning requirements. A "plush" habitability ship would have a greater fraction than a ship designed for "austere" habitability, if manning were constant.

SPICA II has the larger volume fraction allocated to personnel, but at the same time a large personnel carrying capacity. M161 has a significantly lower personnel support

fraction, than the other vessels, as in this ship mission requirements are enhanced instead.

4.3.3 Ship support (V3)

Ship support and ship mobility systems fractions take the largest portion of the volume fraction. This fraction is almost constant at 60% for all the ships studied.

In all the ships the volume fraction dedicated to ship support is held constant around 35%, with the exception of PHM. This is due to the small redundant gas turbines used for power generation, as well as the 400 Hz frequency system used for electrical power, which is smaller and lighter compared to a comparable 60 Hz system.

4.3.4 Ship mobility system (V4)

All the ships use Gas turbines for main propulsion with the exception of APB34. It is proven by various studies that if two boats with the same hull form have the same mobility system fraction, and the one uses diesels for main propulsors and the other gas turbines, the one with the gas turbines will achieve a much higher speed. This is due to the lower volume specific ratio (volume vs power available) of the gas turbines.

The same fraction (approximately 20%) is dedicated to V4 volume fraction to all the ships, with the exception of PHM.

SPICA II, M161, and APB34 have a low fraction of ship mobility system as they have a very compact engine room.

M161 has two small retractable and steerable outdrives used for auxiliary propulsion, which do not affect the size of the engine room. SPICA II has only three small Gas Turbines for boost and cruising speed, and and APB34 two Diesels only. We should note here that there is always a trade-off between the volume dedicated to ship support and the volume dedicated to ship mobility system.

4.4 WEATHER DECK SPACE COMPARLSON.

Weapons, launchers, superstructure, exhausts and intakes, small boats, and replenishment at sea equipment compete for available topside area. This occurs in all naval ship designs and is especially critical in the very small area available on the combatants of our study. It is in this aspect that the SES APB34 has a great advantage. An almost rectangle area of $111 \times 39 \text{ ft}^2$, which allows for great arrangeability of weaponry and communication systems. This in turn, provides for less problems concerning weapons and electromagnetic compatibility. The weather deck space utilization can be found in figure 4.4.

4.4.1 Weapons/ Sensors fraction.

The smallest weapons/sensors fraction can be seen for CPIC, due to small weapon systems. SPICA II has the highest at 42.7%, due to the mine rails and large torpedo tubes. Although the weapons/sensors fraction is only 24% in the APB34 design, the actual area given to weapons and sensors is very large. It is merely shadowed by the exceptionally large deck area.

4.4.2 Superstructure fraction

SPICA II has a very small superstructure located aft of amidships. The superstructure area fraction is significantly higher in the hydrofoil designs, and especially in the PHM, with its large communications and large CIC.

4.4.3 Boats And Replenishment- At- Sea Fraction

Small crews require few life rafts in an emergency. Therefore the boats fraction of the weather deck area is insignificant. Most of the ships have been designed as "day boats", so the replenishment at sea fraction is very small. There is no more than one replenishment stations in each one of them.

The larger replenishment at sea fraction appears in the PHM as expected, due to its long period of mission duration (longer than any of the other vessels).

4.4.4 Intake And Exhaust Fraction

There is a association between the intake and exhaust fraction and the Shaft Horse Power per displacement for each ship. The higher the main propulsion ship-size ratio, the larger area fraction that is needed for intakes and exhausts.

4.5 CHAPTER CONCLUSIONS

The major design differences have been identified in this chapter. A conclusion common for all ships is that mission drives weapons systems enhancement, which usually requires more space. Speed needs more weight and space. With speed, range at high speed, and payload being the three most important factors, sacrifices must be made elsewhere. The next chapter will try to explain how different philosophies drive the certain designs, and where the sacrifices are made to enhance mission area. It will analyze the trends by ship size or mission inherent to the small combatants of this study.

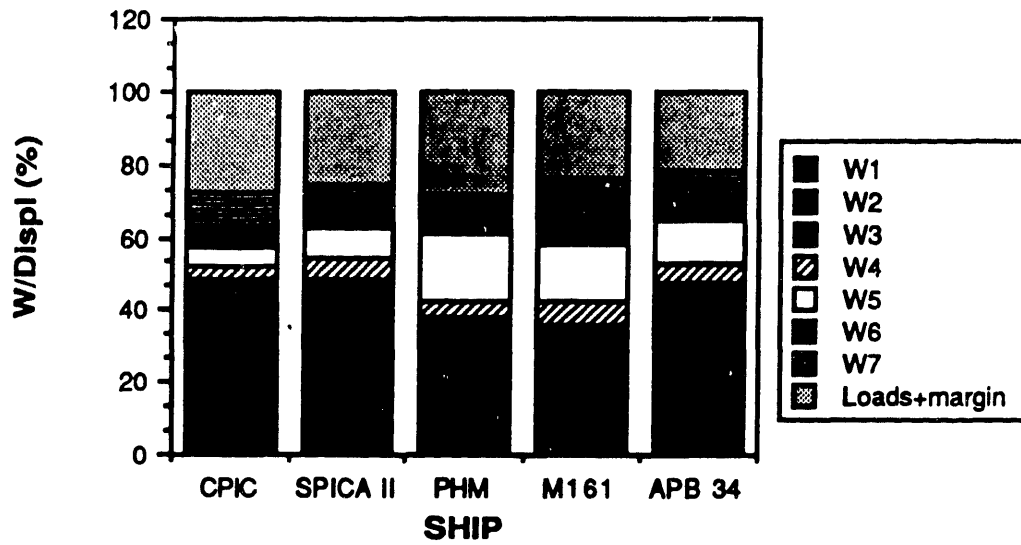
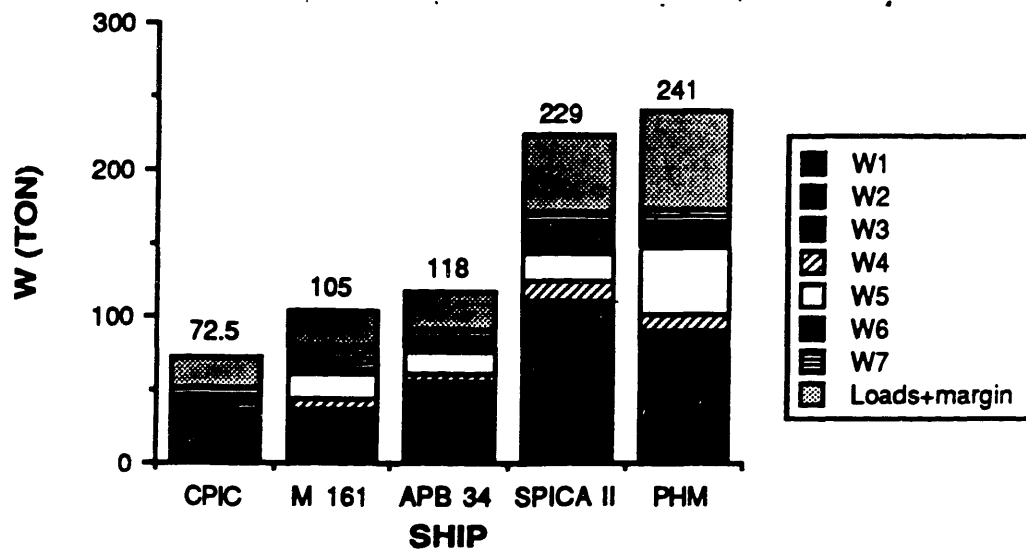
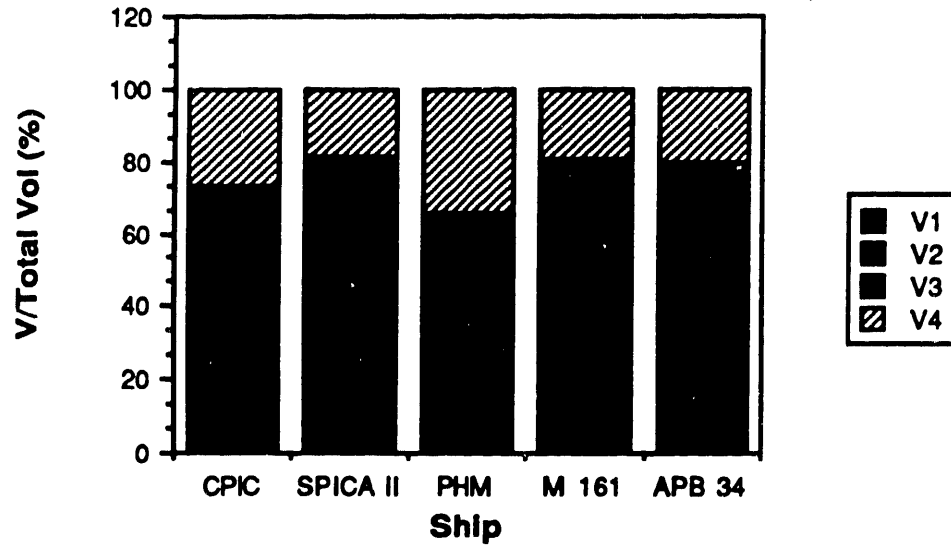
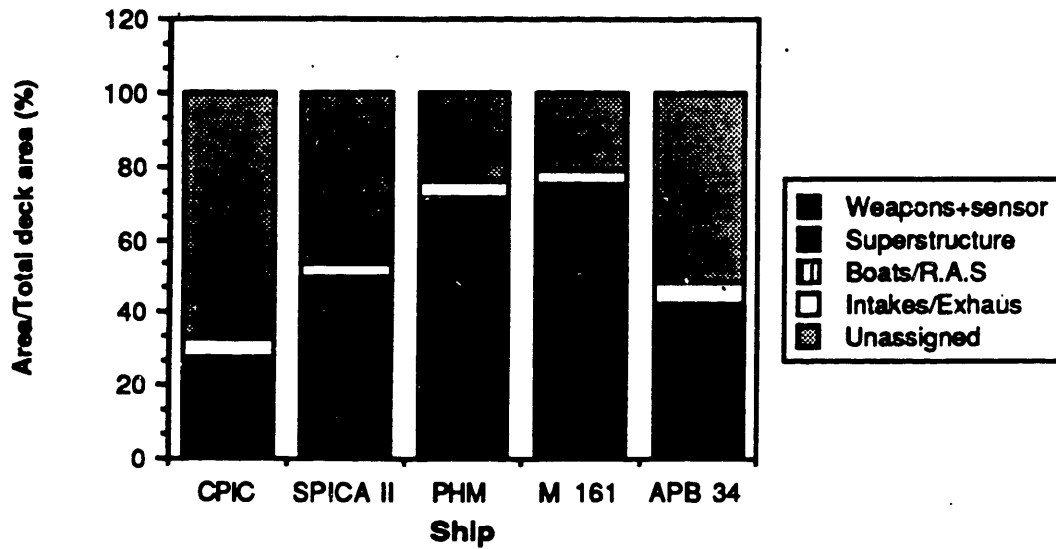
Fig. 4.1 Weights fraction**Fig. 4.2 Full load weights**

Fig. 4.3 Volume allocation**Fig 4.4 Weather deck space utilization**

CHAPTER 5

DESIGN INDICES BY FUNCTIONAL AREA

In this chapter a further analysis of the findings of chapter 4 are discussed. Each different type (monohull, hydrofoil, SES) has its own characteristics. Likewise, every design feature is affected by the design philosophy of the country the vessel was built for, the size of the vessel, and the mission for which the vessel was designed.

The functional areas in which the vessels were divided are the following:

Mobility

Structure

Electrical power

Payload

Command and Surveillance

Ship operations

Auxiliaries

Outfit and furnishings

Personnel

5.1 MOBILITY

Even though effective modern missiles are capable of being launched over-the-horizon, it is necessary to know what is being targeted. To assure that missiles fired will attack high-value units of an opposing force, it may be necessary to close to relatively short range. Thus, tactics which take advantage of the speed and maneuverability of the small Naval combatants are desirable. Speed and maneuverability, along with endurance, seakeeping, and flexibility of the various designs in the study are included under the title of mobility.

The issues of speed, range, seakeeping, and design integration standards are analyzed in the following paragraphs, in order to understand how each one of them drives the philosophy in the design of the different ships.

5.1.1 Speed

The speed characteristics of the ships can be found in table 5.1. The fastest ship is M161, and the slowest SPICA II. In SPICA II greater emphasis is given to her anti-submarine warfare role, especially after the major modifications of 1984. When on anti-submarine operations, SPICA II does not need to use all its speed, as the sonar effectiveness becomes limited when operating above 25 Knots.

Small ships need to be fast as possible, in order to be effective in their "guerrilla warfare" role, and to protect themselves against any type of attack, as they lack sophisticated self-defense systems.

TABLE 5.1

SPEED CHARACTERISTICS

SHIP	CPIC	SPICA II	PHM	M161	APB34
Δ (tons)	72.5	229	241	105	118
Hull type	Planing	HSD	Hydrofoil	Hydrofoil	SES
Plant	OODOG	GT	OODOG	OODOG	Diesel
Maximum speed (knots)	45	40.5	50+	52	45
Lift/Drag	~7	~10	~13	~10	~17
Prop Coef	0.45	0.62	0.44	0.67	0.60
(L/D) \times (P.C)	3	6	6	7	10
Main propulsion wt spec. ratio (Lb/HP)	4.1	3.6	3.2	3.9	4.9
Main propulsion wt fraction (%)	15.9	9.0	14.2	9.5	9.5
Main propulsion ship size ratio (HP/Ton)	82.8	56.3	70.5	51.4	46.6

Speed is affected by different design features. It can be written as a fraction of:

$$\text{Speed} = \frac{(\text{Design Budget}) \times (\text{Hydrodynamic Effic.})}{(\text{Design Standard})}$$

The design budget is a function of the main propulsion weight fraction. The hydrodynamic efficiency is a function of the Propulsive Coefficient and the Lift-to-drag ratio. Finally, the design standard is a function of the main propulsion specific weight ratio.

From the above relation we can see that a large propulsive coefficient, and Lift to Drag ratio are in favor of a speedy ship. Light propulsion components, as well as powerful and light engines drive the speed of a vessel up.

5.1.1.1 Hydrodynamic Efficiency

Hydrodynamic efficiency plays a significant role in the production of speed, and it is a function of the propulsive coefficient and the lift to drag ratio.

5.1.1.1a Propulsive coefficient

The propulsive coefficient is the ratio between the power required to tow the ship at the designed speed, the Effective Horsepower, and the power measured in the shafting within the ship, the Shaft Horsepower. Thus it is

actually an indicator of the efficiency of the propulsor hull interaction. It is desired to have the largest possible PC, thus maximizing the speed for a given Shaft Horsepower.

The propulsive coefficient of all the ships is around 0.63 with the exception of the small CPIC and the PHM. PHM uses a single two stage waterjet as a foilborne propulsor, which contributes to a reduction in propulsive coefficient of about 20%. The reduction of the propulsive coefficient of PHM is the trade-off to the reduction of the noise emitted by the propulsion system.

5.1.1.1b Lift to drag ratio.

Lift to drag ratio (L/D) is actually the ratio between the ship full load displacement and the ship's drag at the speed the ratio is calculated. For the hydrofoils the powered dynamic lift, and for the SESs the powered static lift created by the foils or the lift system, correspondingly, is added to the full load displacement, making this ratio rise. Dynamic lift is created in the planing craft at high speeds, thus raising their L/D ratio.

Hydrofoil craft suffer practically no wave making resistance when foilborne, and since the only wetted surface is that of the foils and struts, they have also frictional resistance. As a result, for the same total weight and power they can achieve speeds higher than the comparable high speed displacement or planing hulls. Before being foilborne, they experience drag both from main hull and from the foils and struts, and have a "hump" in the resistance curve, which is taken into consideration, as far as the take-off speed and installed horsepower are concerned.

A fundamental limitation is imposed here by the so called "square-cube" law, which impacts the growth potential of hydrofoil ships. Because the lift developed by the hydrofoil ships is proportional to their wing area (the square of the linear dimension), it follows that as the size is increased the foils tend to outgrow the hull. The same problem exists in aircraft, but it is solved by increasing speed and wing loading as size is increased. However practical hydrofoil speeds are limited by cavitation.

In the APB34, a SES, the cushion of air raises the ship up on the water, minimizing the contact between the hull and the water. This results in a substantial decrease in the total resistance. As happens with the hydrofoil design, lower drag permits higher speed for a given power.

The vertical accelerations, resulting from the response of the SES to wave excitation, are of primary importance, since the the relative motion between the keel of the sidehulls and the water surface will determine the extent of air leakage from the cushion. Similarly, the motions will affect the leakage below the seals at both the bow and stern. Whenever air leakage occurs the vessel will sink deeper into the water, thereby resulting in increased drag of the immersed portions, that is, propulsive drag. In addition, the system must make up for some of this loss, and hence there is additional power requirement associated with the lift fan operation for this case. There is a trade-off between the extent of immersion necessary to maintain the cushion and the resulting propulsive drag from immersion, which manifests itself in the case of motion in waves, as well as under static performance conditions.

CPIC has the lowest lift-to-drag ratio due to its small size.

Summarizing, the hydrodynamic efficiency of APB34 is higher than the hydrodynamic efficiency of the other ships. The hydrofoils and SPICA II have approximately the same product of L/D and P.C.. The CPIC pays the penalty of its size, having a hydrodynamic efficiency around 3.

5.1.1.2 Main Propulsion Weight Specific Ratio

The main propulsion weight specific ratio is a measure of the overall weight to propulsion power efficiency of the propulsion plant. A lower ratio indicates that the plant will provide more power for a given propulsion plant weight, which may allow for an increase in ship speed without an appreciable effect in displacement, or may allow for a decrease in the physical size of the plant.

The small combatants of the study have advanced technology propulsion plants in order to save weight. For this reason the small vessels having extremely lightweight plants, have significantly lower W_2/SHP ratio than other bigger ships, which need more flexible and rugged propulsion plants to fulfil their longer missions. The weight saved in the plant allows higher speed and at the same time an increased proportion in the weight fractions of the other vital ship areas.

The selection of Diesels as propulsion engines for the APB34 drives the main propulsion weight specific ratio up (see figures 5.1, and 5.2), since the diesels are heavier than gas turbines for the same delivered power. So, the effect of the large main propulsion weight specific ratio, of APB34 neutralizes the advantage of the high propulsive efficiency, making the ratio of the propulsive efficiency

over W_2/SHP similar to that of the other ships, as can be seen in figure 5.3.

PHM has a very low main propulsion weight specific ratio, necessitated by the trade-off of the lower propulsive efficiency, due to its lower propulsive coefficient. This trade-off is apparent in the other designs as well, as can be seen from figure 5.3. Excluding the inefficient small CPIC all the other ships have approximately the same ratio of Propulsive Efficiency over main propulsion weight specific ratio, living the achievement of a higher speed to the design budget.

5.1.1.3 Design Budget

For a certain ship, the higher design budget is in favor of a higher speed.

The design budget versus speed relation can be seen in figure 5.4. The CPIC has the highest ratio due to its heavy transmission system for its size. Although PHM has only a Gas Turbine for propulsion and a light transmission, the water used for the foilborne or hullborne waterjets, and the two diesels used for hullborne propulsion drive the W_2/D ratio up. The other three ships have a main propulsion weight fraction constant around 9.5.

5.1.1.4 Conclusions

The discussion of the previous paragraphs indicate the high cost of CODOG plants and Diesel Propulsion. Due to the neutralization of high propulsive efficiencies from high main propulsion specific ratios, the most important indice,

as far as speed is concerned is the main propulsion weight fraction. So speed costs, as we need a higher W_2/Δ to achieve a higher speed.

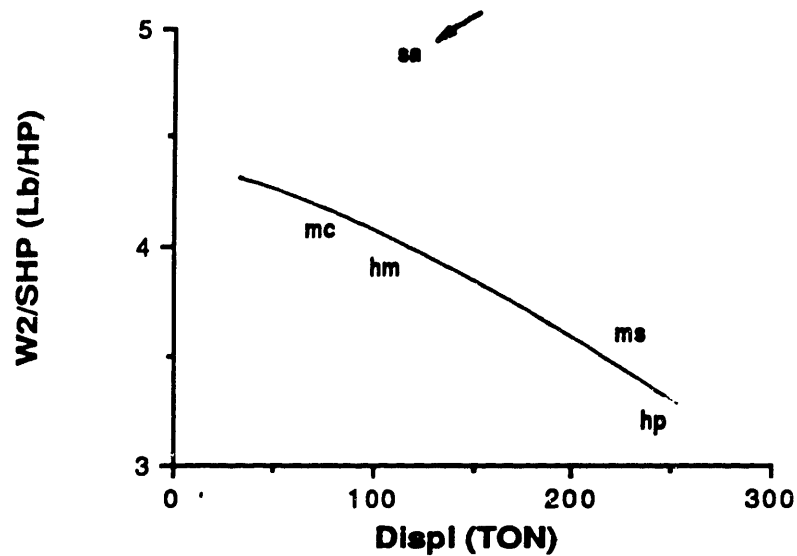
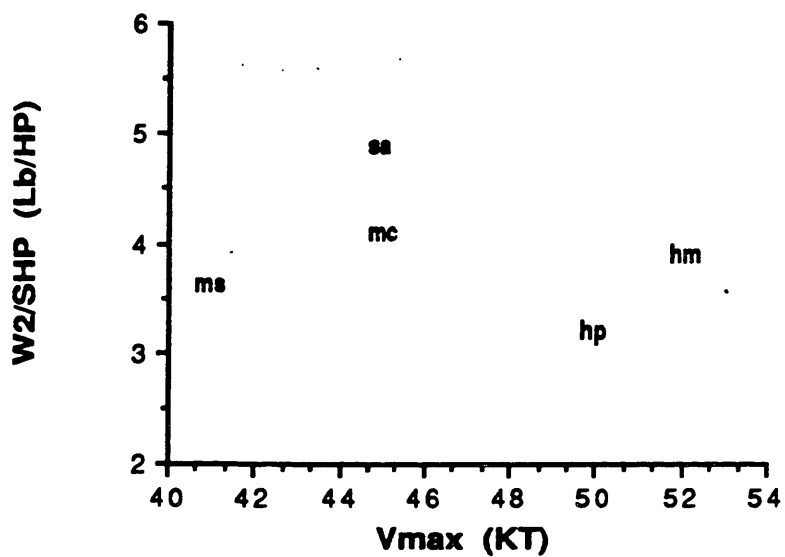
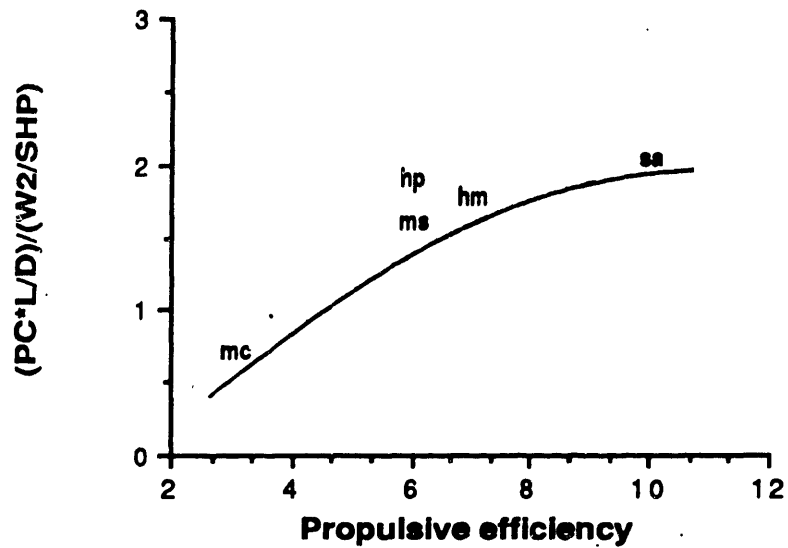
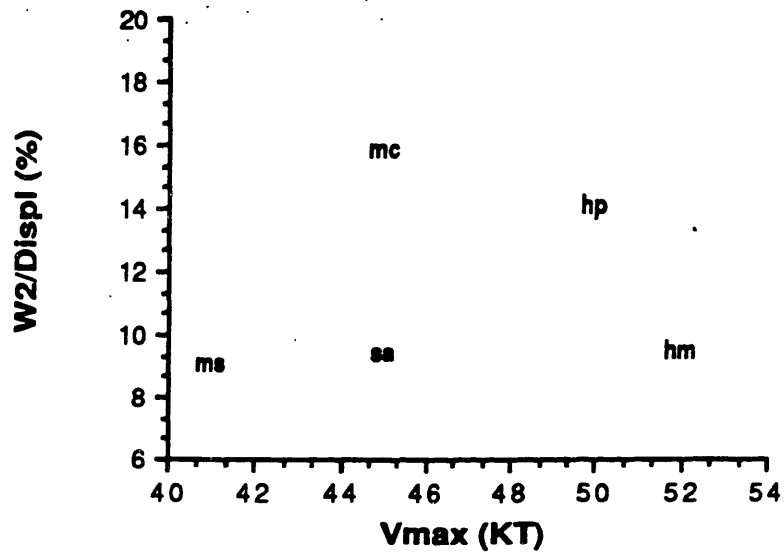
Fig 5.1 Main propulsion wt spec. ratio vs. Displ**Fig. 5.2 Main propulsion spec. wt vs. max speed**

fig 5.3 $(PC \cdot L/D)/(W_2/SHP)$ vs Propulsive Effic.**Fig. 5.4 Main propulsion wt fraction vs. Max speed**

5.1.2 Range

At sea all the ships run out of fuel before the stores limit is reached. The ship with the longest endurance is PHM, which with a replenishment at sea can extend its sailing days to limits reached from much larger combatants. With three under way refuelings PHM is capable of crossing the Atlantic from Massachusetts to United Kingdom at an average speed of 30 Knots in 4.2 days.

5.1.2.1 Stores endurance

PHM and CPIC, the two U.S. designs, are provided with stores' spaces that can support the personnel for more than a day ($2\frac{1}{2}$ for CPIC and 5 for the PHM). Although no data exist for SPICA II, after measuring its stores' spaces capacity, it is assured that she can be at sea for more than 4 days before her stores limits are reached.

5.1.2.2 Fuel endurance

Fuel endurance is a function of speed, propulsive coefficient, fuel weight, Specific Fuel Consumption, and Effective Horse Power at endurance speed.

Short missions characterize the small combatants of our study. These short missions are due to the need of less time at sea under the eye of the enemy. No data for range at maximum speed were found. This information is kept proprietary or is classified by the different navies.

Accuracy in the endurance calculations of the designs of the study was not easy to obtain. Ranges for each ship

can be found on Table 4.1 for a speed around 16 Knots. The range of M161 at 16 knots could not be estimated, but it seems that it is smaller than that appearing in table 4.1 at 42 knots, due to the high SFC of the Gas Turbines in slow speeds, and the large drag as at the speed of 16 knots, as at this speed M161 is operating hullborne.

Fuel endurance may be found from the following relationship:

$$R = \frac{(V) \times (P.C.) \times (W_{FUEL})}{(SFC) \times (EHP)} = C \times (L/D) \times (WF/D) \times \frac{1}{(SFC)}$$

Where C is a conversion factor.

So Range could be written as:

$$R = (\text{Design Budget}) \times (\text{Hydrodyn. Effic.}) \times (\text{Design Effic.})$$

The small L/D ratio of CPIC as well as its small size and its small installed SHP make its fuel endurance the smallest of all the other ships.

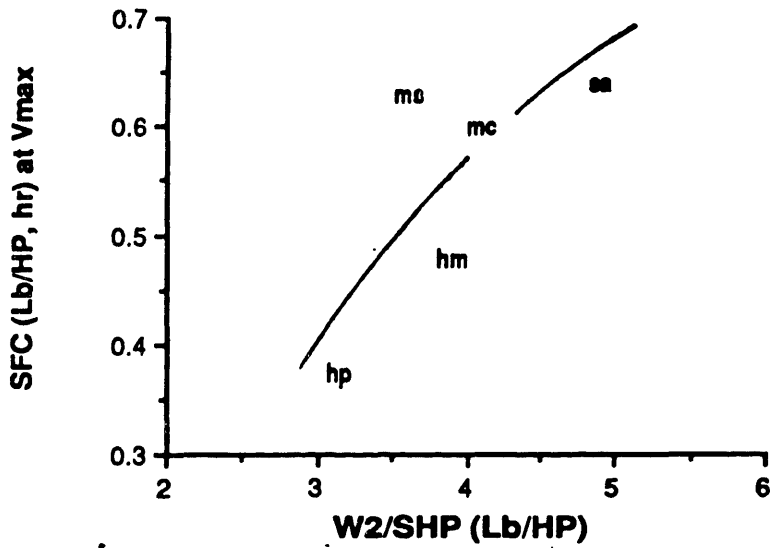
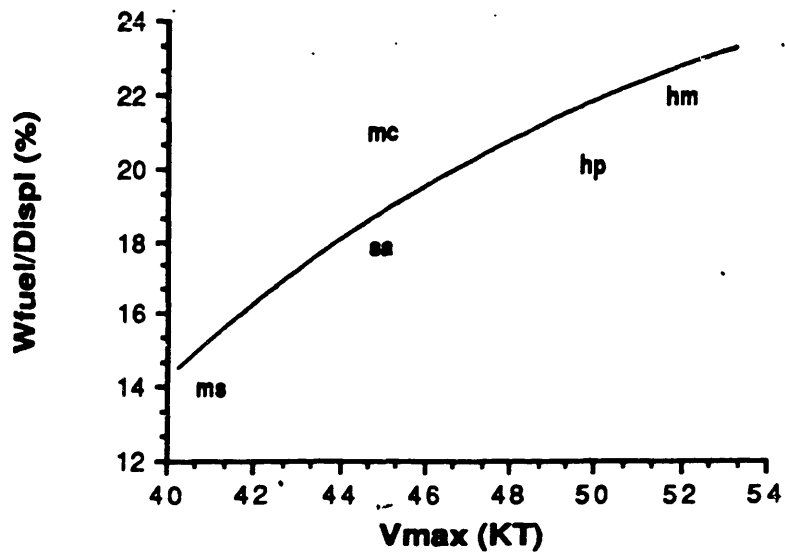
There is always a trade-off between payload weight and the weight of the fuel a vessel can carry (its design budget), and thus its range. For example the fuel weight, M161 can carry ranges from 16 to 21 tons, thus extending its range from 750 to 1150 Nm., depending on its mission and the amount of crew aboard (4-15).

Ships with higher main propulsion weight specific ratios, tend to have higher SFCs at maximum speed, as can be seen from figure 5.5. This is due to the upward trend of

the Specific Fuel Consumption at maximum speed as W_2/SHP_B is increased. There is also a mission trend concerning the fuel weight that can be carried aboard the ships. (See figure 5.6). The more speedy the ship, the higher the fuel weight fraction.

5.1.2.3 Conclusions

Design budget of fuel weight is the most important method to get a longer range. Range and mission length are critical to fuel cost. Efficient design standards and hydrodynamic efficiency also play an important role. Finally, it can be assumed that stores endurance does not normally limit the ships operation, as every ship reaches the fuel limit first.

Fig. 5.5 SFC vs Main propulsion wt spec. ratio**Fig. 5.6 Fuel wt fraction vs. max speed**

5.1.3 Seakeeping

The seaworthiness of a hull form is related to three factors: The wave response characteristics of the ship, the nature of the wave environment, and the ship's speed and heading.

The limiting factors for heavy seas are military performance, crew performance, structural load limit and powering limit. Figure 5.7 shows this speed-wave envelope for a typical military vessel. It can be seen that ships slow down first due to the degradation of military effectiveness. In the following pages the factors that enhance ship performance and maneuverability in calm and heavy seas are introduced.

For small combatants, the final measure of seakeeping is the speed the ship can sustain in rough seas without severe slamming and deck wetting. The greatest single influence on the seakeeping ability of a conventional ship is its size as characterized by its length, and especially the slenderness ratio ($L/V^{1/3}$). A slenderness ratio of 7 or more is considered sufficient to counter slamming. SPICA II and CPIC have a slenderness ratios of 7.2 and 7.3 correspondingly. CPIC and SPICA II use a deep Vee forward of about 40° to reduce pitch and heave. CPIC uses also a Vee aft to the transom of about 12° to further reduce slamming and heave.

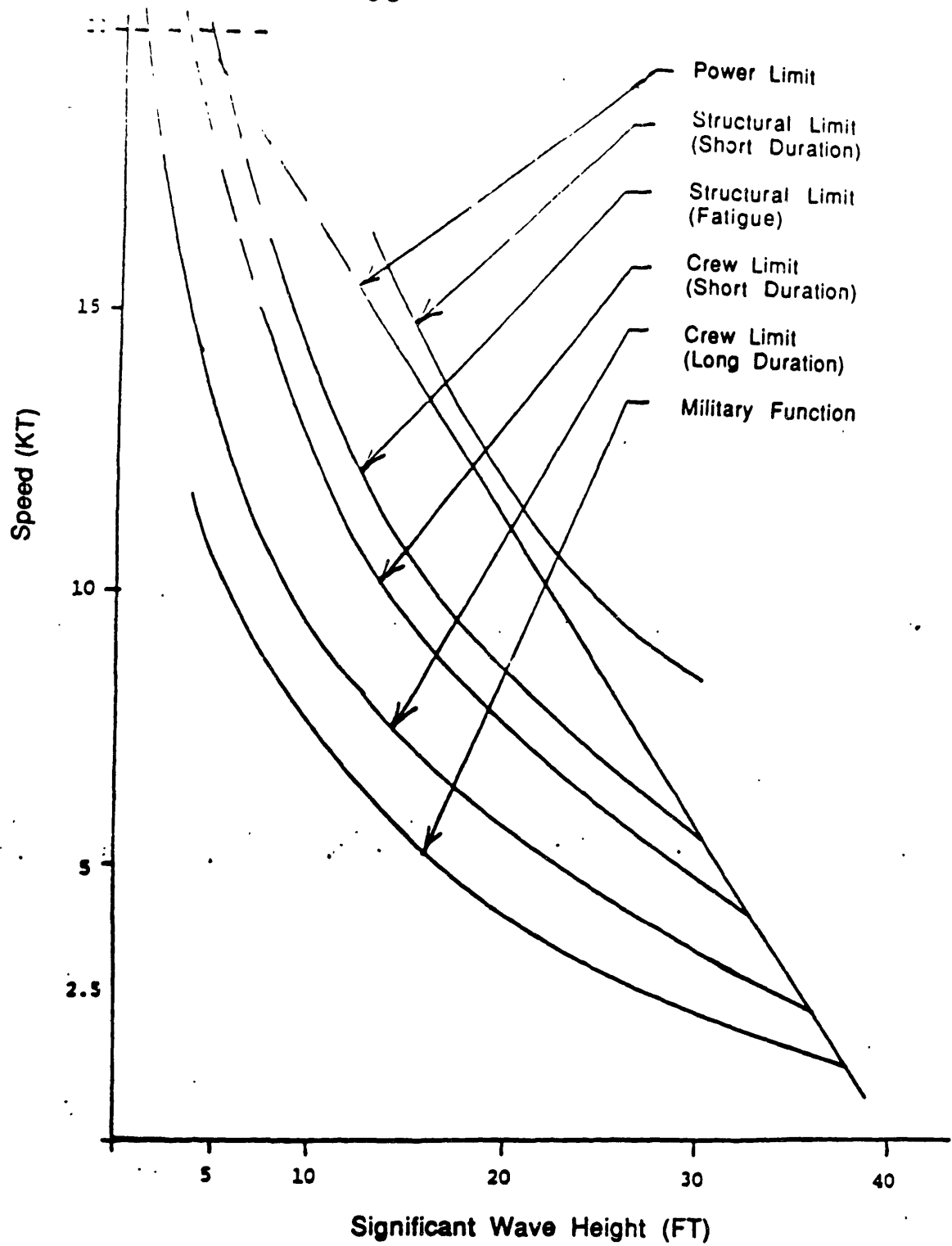


Fig. 5.7 Speed wave height envelope.

The use of the lifting surfaces on PHM and M161 reduces the effect of waves on these ships. The reaction of these surface piercing hydrofoils to waves is substantially less than for the high-speed displacement SPICA II or the planing hull of CPIC. But the requirement for ship motion to balance the disturbing forces caused by the waves, coupled with geometric limits to a practical design, restricts the sea states in which high speed operation can be considered acceptable. For this reason, PHM and M161 augment their stability by the mutual interworking of the submerged foils with the ship's automatic control systems (ACS). The ACS provides continuous dynamic control of the ships during take-off, landing, and all foilborne operation. In addition to providing the ship's roll and pitch stability, the ACS controls the height above the water surface, causes banking in turns and eliminates ship motions caused by orbital particle motion of the waves. The ship hull operates above the effect of the surface waves. The foils that provide lift and control forces operate below the water surface where wave effects diminish with depth. Foilborne operations only become limited as the wave heights exceed the hydrofoil strut length. The result is an exceptionally smooth operating environment for crew and combat systems equipment. Less well realized is the major contribution of the foil systems to motion reduction when hullborne. The foils act as dampers which significantly reduce motions in both the roll and pitch modes.

Figure 5.8 shows the reduction of ships' speed as a function of the significant wave height. These data clearly show the ability of the hydrofoil ships to maintain speeds over 40 knots in rough seas.

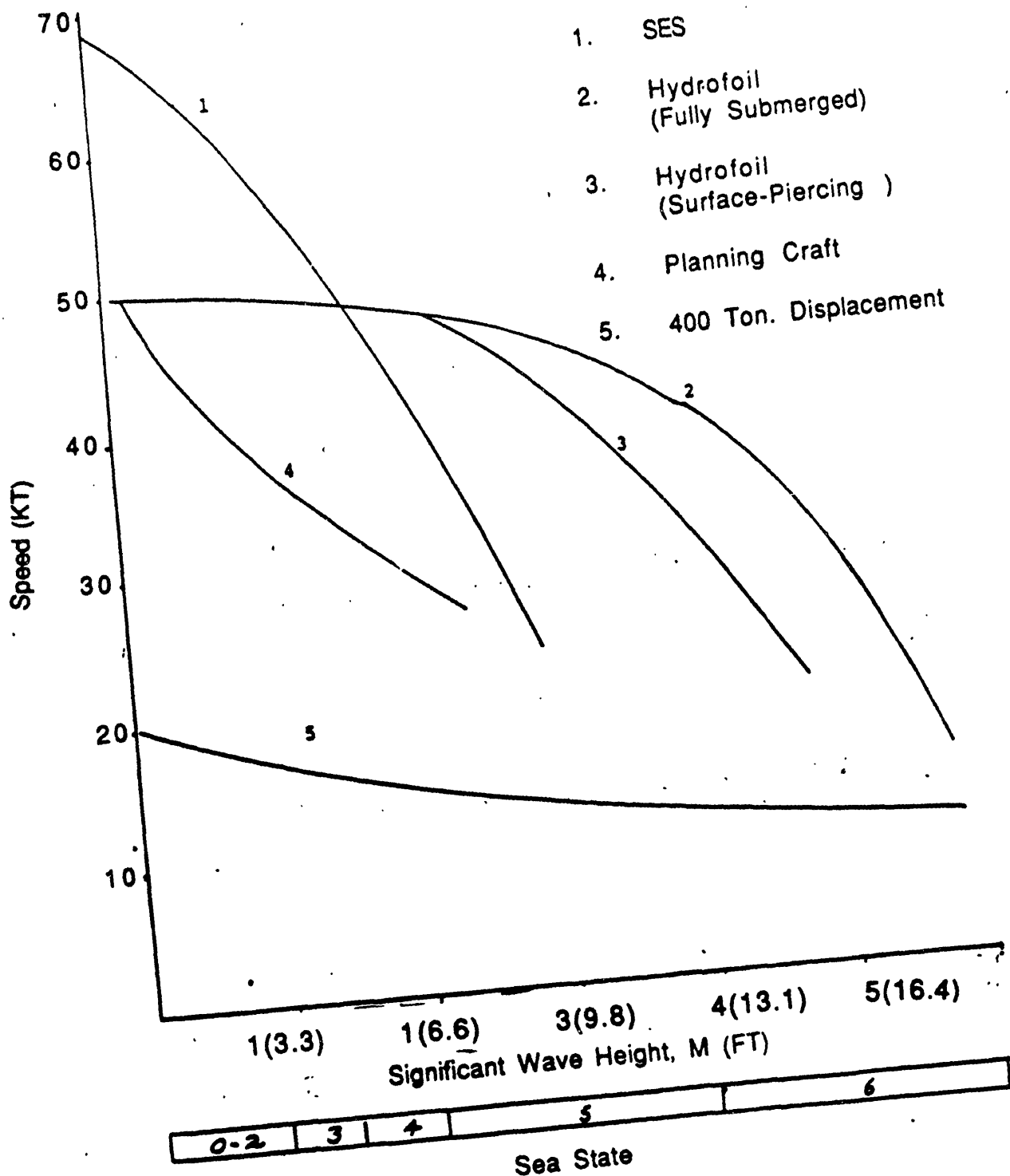


Fig. 5.8 Speed vs. Wave height.

The ships' crew response is dependent on the direction, magnitude and frequency of the motion of a ship and, in particular its vibration. In ships, vertical motion is the primary known cause of motion sickness, while both vertical and lateral acceleration are major contributors to fatigue. The magnitude and frequency content of the vibration determine how long the human can tolerate a given level before becoming sick or before proficiency is impaired by fatigue. Figure 5.9 shows the data base for human response to vertical acceleration in terms of frequency and exposure time. PHM and M161 operating at 40

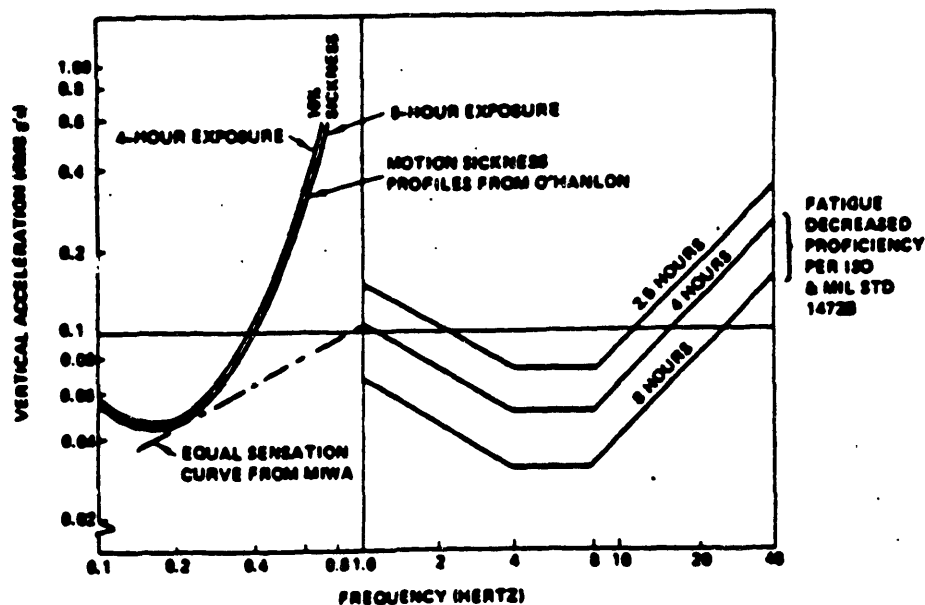


Fig. 5.9 Data Base for human response to vertical accelerations (Source: Johnston R. J., "Hydrofoils", Naval Engineer's Journal, Feb. 85).

knots in head seas will encounter waves every 1 to 2 seconds depending on wave period.

The commander of a conventional ship, unwilling to subject his ship or his crew to punishment of the rough seas, will slow down to the "good practice" limit of one slam per minute (0.017 Hz), a wave encounter frequency below the data base.

In order to reduce rolling CPIC uses a hard chine, Vees forward and aft, and transom fin stabilization.

SPICA II has a deep keel, a semi hard chine, and a deep Vee forward.

The APB34 does not have a sharply pointed slender bow and a deep draft commensurate with its size. Instead, it is supported on an air cushion which reduces draft, lowers overall resistance and ship motions, and increases performance.

The cushion height is determined by the desire to have it exceed the majority of waves encountered in the proposed operating environment and to satisfy transverse stability considerations.

APB's plenum under the hull serves as a passive motion-damping accumulator that significantly reduces motions in large seas.

When APB34 is operating in the hullborne mode, it tends to have approximately the same freeboard as similar sized monohulls. However, when on cushion, freeboard increases dramatically by a factor of 2. On cushion, the wetdeck is sufficiently high to greatly reduce the structural bending moments and permit high speed operations in high seas without slamming. This high on-

cushion freeboard also provides safe dry decks in high sea states.

In the CPIC deck wetness is mitigated by the use of double hard chines which reduce spray. SPICA II uses flare and spray chines.

When operating on cushion, the lift system with active ride control provides a very good ride when compared to a monohull of equivalent size. Typically, as verified by model test and full scale trials, SESs do not experience hull slamming until the significant wave height exceeds the wetdeck height. The physical reason for this capability is that, unlike a monohull or hydrofoil which rides about the mean draft at about the middle depth of the hull, strut, or foils, an SES operates with the mean waterline close to the keel. This provides significantly more freeboard and clearance than an equivalent size monohull displacement ship. The SES pneumatic ride control system operates effectively at all speeds and headings in either a platforming or contouring mode.

This seakeeping, when combined with the low pitch, roll, and heave motions of an SES (which are typically 1/2 to 1/3 of those of an equivalent monohull), make SESs attractive candidates for missions that require operation in areas where sea states 5 or 6 occur significant percentage of the time.

The vertical plane motions of heave and pitch for APB34 are influenced primarily by waves. The motions are not the only aspect to be considered, but also the vertical accelerations. These vertical accelerations affect the basic ride quality, which has a significant influence on the performance of various subsystems on the craft. Likewise, the vertical accelerations in higher frequency range caused

by high speed can be irritating if not adequately regulated. The current generation control systems attempt to maintain constant cushion pressure and are very successful at it. However, the contributions to accelerations such as hydrodynamic sidehull and seal forces together with the impact of very long ocean swells are not currently controlled, and an improvement of control systems is needed.

5.1.3.1 Maneuverability

Besides the significant speed advantage, hydrofoils are more maneuverable and provide more stable platform than conventional ships. Foilborne turns are accomplished in a banked (coordinated) fashion. This causes the centrifugal force required in turns to be provided predominantly by the reliable lift capability of the submerged foil rather than the unpredictable side forces from the surface-piercing struts. Turn coordination enhances crew comfort during high-rate turns because the accelerations due to turning are felt primarily as slightly greater vertical forces rather than lateral forces. Therefore hydrofoil ships have design turn rates of 6 to 12 degrees per second, two to four times those of conventional ships, and they can maintain these rates in both calm and rough seas. This makes the hydrofoil ship a more difficult target for enemy missiles, guns, and torpedoes. But in order to obtain this outstanding rough water behavior, the construction budget of the hydrofoil is increased due to the need of the foil system with its relatively complex strut, foil and flap structures, automatic control systems and high power hydraulic actuation systems.

5.1.3.2 Conclusions

More information is needed in order to accomplish a detailed seakeeping or maneuverability analysis, for the vessels of our study. Roll, heave, pitch periods are needed, as well as major other parameters as acceleration responses, power spectrums etc.

Hydrofoils have the best seakeeping capability and maneuverability of all the ships. SESs come next, with the disadvantage of irritating vertical accelerations at high frequencies. (Reference 40)

5.1.4 Propulsion System Design Integration

The major elements of a ship's propulsion system are the prime mover, the transmission and the propulsor. Critical factors affecting the selection of the propulsion system include top and cruise speeds, ship size, range and endurance, hull geometry, engine matching, draft, vulnerability and maneuverability. For high-performance ships sufficient power must be available to permit the ship to traverse the hump and achieve design speed. To establish installed power and fuel requirements for specified performance levels, it is necessary to estimate the individual efficiencies of the elements.

After knowing the power and the efficiencies of the various propulsion elements, their integration is needed in order for the designer to be able to install them on the ship. The way engines and other propulsion components are selected, and located within the ship affects all other ships characteristics. Once speed and size have been established, the propulsion system weight and volume requirements can be delineated. But space, volume and weight devoted to propulsion takes away from other vital ship functions. Thus, propulsion plant integration is iterative in nature.

The following pages present why different propulsion systems are selected for each ship, and discuss how this selection is driving weight and volume allocations as well as propulsion operability and survivability.

The propulsion systems characteristics of the vessels of the study can be found on table 5.2.

TABLE 5.2

DESIGN INTEGRATION PARAMETERS

SHIP	CPIC	SPICA II	PHM	M161	APB34
A. VOLUME					
Main propulsion volume fraction (%)	26.8	19.1	34.4	19.5	20.0
Main propulsion spec. ratio.(ft ³ /HP)	0.47	0.43	0.67.	0.57	0.86
B. WEIGHT					
Prime mover wt fraction (%)	45.5	22.3	19.9	18.0	40.8
Transmission wt fraction (%)	29.5	40.6	24.0.	55.6	24.0
Support wt fraction (%)	20.0	14.7	13.2.	16.3	14.0
Other prop. wt fraction (%)	5.0	22.4	42.8	10.1	21.2

Main propulsion density (Lb/ft ³)	11.3	2.2	2.5	6.6	5.3
Main propulsion wt fraction (%)	15.9	9.0	14.2	9.5	9.5
Main propulsion wt spec. ratio (LB/HP)	4.1	3.6	3.2	3.9	4.9
Total HP ship					
size ratio (HP/Ton)	87.9	56.3	77.2	53.9	46.6
Main propulsion ship size ratio (HP/Ton)	82.8	56.3	70.5	51.4	46.6
Transport efficiency (Ton*knots/HP)	0.51	0.72	0.64	1.01	0.84

The Brake Horse Power (BHP) is of prime interest since it dictates the propulsion engine selection. The BHP is given by

$$\text{BHP} = \frac{(T_n) \times (V)}{550 \times (PC) \times (n_T)}$$

Where T_n is the net propulsor thrust (after accounting for propulsor mounting and ship interaction losses), V is the ship's speed, PC the propulsive coefficient, and n_T the transmission efficiency.

From examination of figure 5.10, it can be seen that less propulsor thrust is needed by the hydrofoils and the APB34, in order to achieve their maximum speeds compared to monohulls of the same size. PHM for example achieves 40 Knots using 11,000 SHP while SPICA II, a monohull of the same displacement, uses 12,900 SHP.

5.1.4.1 Prime Movers

APB34 uses two diesels at 5,500 SHP as prime movers. All the other ships are driven by gas turbines. CPIC uses three gas turbines at 6,000 SHP, SPICA II three at 12,900, PHM one at 17,000 SHP, and M161 one at 5,400 SHP.

The weight of the propulsion plant itself is a crucial consideration in the design of a vessel, since higher propulsion plant weight fraction favors speed. But as speed increases and of course becomes costly, weight is deprived from all the other ship functions. The measure of the propulsion plant weight efficiency is the main propulsion weight specific ratio in pounds per SHP. The Diesel-

powered APB34 derives less power from the amount of weight used for the propulsion plant, than the other ships (see figure 5.1). All the other vessels having gas turbines as prime movers, have lower specific weights. The lowest is that of PHM with the LM2500 driving the 241-ton hydrofoil at a speed in excess of 50 Knots.

As the fuel weight is a very significant consideration in the ship design, the power plant must have a low SFC to minimize the fuel weight carried on board. SFC reflects the operational efficiency of the ship's power plant. Its determination is basic to accurate estimation of the fuel required for operation in various sea states and at different ranges. The SFC of Marine engines varies with engine revolution per minute (RPM), and power level. The SFC of the ships of the study varies between 0.38 and 0.64 (Pounds per HP-hr), at maximum speed. The LM2500 of PHM has the best operational efficiency, while the MTU Diesels of APB34 the higher SFC.

The association between SFC and main propulsion weight specific ratio can be found in figure 5.5. A larger data base is needed to determine if there exists a trend between SFC and W_2/SHP .

5.1.4.2 Transmissions

For small FPBs the selection of the light weight transmission systems is of prime importance. Of secondary importance are high efficiency, flexibility, reliability (which is related to higher weight), and simplicity. Other desirable characteristics include maintainability, low volume, and low noise levels.

APB34 and the two monohulls drive their propellers through reliable V-Drive transmission systems. The diesel-driven APB34 has a small transmission weight fraction (20%). SPICA II, with its higher-rated Gas turbines uses a large proportion of weight, 41%, for its transmission system, due to the need to handle higher engine power than the other three ships. CPIC allocates the 29.5% of its propulsion weight for power transmission. M161 has a V-Drive transmission and a Z-Drive to transfer the main engine power to the propeller, and its transmission weight fraction is the largest of all five vessels (55.5%). PHM has two small sets of reduction gears to drive its waterjet, and only 24% of its propulsion weight is allocated for transmission.

5.1.4.3 Propulsors

M161 uses a four-bladed controllable-pitch propeller in order to fulfill the requirement of variation in advance coefficient due to the resistance of the ship at hump speed and the variation of resistance due to the environment and loading conditions

SPICA II, CPIC, and APB34 use supercavitating CRP propellers. Supercavitating propellers are designed to operate acceptably in the high-speed range by operating with a fully developed blade cavity.

The waterjet propulsor of PHM is more complex than the open propeller due to the greater number of components involved. It has also lower propulsive efficiency in the range of 50 Knots as compared to fully submerged supercavitating propellers, and relatively low thrust at take-off. But by the use of the waterjet the designer

avoids complex transmission systems, such as the Z-Drive configuration.

The efficiency of the propulsion plant of M161 can be seen in figure 5.10. APB34 has a small main propulsion ship size ratio, with the use of the two diesels, but a lower speed. The most inefficient vessel is CPIC. A lot of SHP is needed to drive this small size vessel at a speed of 45 knots. Here we can find a discover a size trend, which is the opposite from compared to the size trend for large ships. Excluding the inefficient CPIC, SHP/ Δ tends to increase as the displacement of the vessels becomes bigger. (See figure 5.11)

Another measure of the efficiency of a propulsion plant of a ship is its transport efficiency. A more efficient ship has the higher transport efficiency, which is in favor of carrying a large full load weight with a high speed, using small SHP (see figure 5.12). M161 could be characterized as the most efficient vessel as far as transport efficiency is concerned. Figure 5.13 shows a transport efficiency trend. Vessels with higher transport efficiency tend to have lower main propulsion weight fraction.

5.1.4.4 Volume allocation

M161, APB34 and SPICA II have compact arrangements. The main propulsion volume fraction versus displacement for the vessels of the study can be found in figure 5.14. The small CPIC uses a larger proportion of its volume for its propulsion plant. The largest volume fraction is that of PHM, partly due to the large auxiliary propulsion system,

which occupies a lot of space as can be seen from figure 5.19.

The two Gas turbine driven monohulls use less space for the propulsion power delivered. The diesel-driven APB34 uses a larger volume primarily due to the larger volume of its medium speed Diesel, as compared to the volume of the gas turbines of the other ships.

There is a size trend, as far as main propulsion density (the weight of the propulsion machinery, divided by the volume occupied by it) is concerned. As the displacement of the vessels of our study increases, their main propulsion density decreases. (See figure 5.15)

5.1.4.5 Survivability

PHM's main and auxiliary propulsion units are located at the same area. Its two Gas turbine-driven service generators are well separated. One is located in the main engine room and the other in the auxiliary machinery room in the aft part of the superstructure. This provides protection against fire only. PHM like all the small ships of our study, is not likely to survive a hit from conventional missile warhead.

The smaller ships, CPIC, M161, SPICA II and probably APB34 have both their main and auxiliary propulsion units as well as their generators located in the same space. This offers much less redundancy, but is necessary given the small size of the ships.

5.1.4.6 Operability

All the ships of the study are difficult to repair at sea. Due to their short mission, they are designed with the philosophy of repair at home port. Only small space is provided for the crew to perform any major repair work at sea. As can be seen from figures 5.16 through 5.19, the machinery components of the ships are packed into a small area. It is important to save space for other ship functions.

5.1.4.8 Conclusions

Space and weight are two very critical factors for the small ships of our study. High speed needs design efficiency and a lot of power. But the requirement to put as much power into as small a space as possible runs counter to the ease of maintainance, survivability and ruggedness.

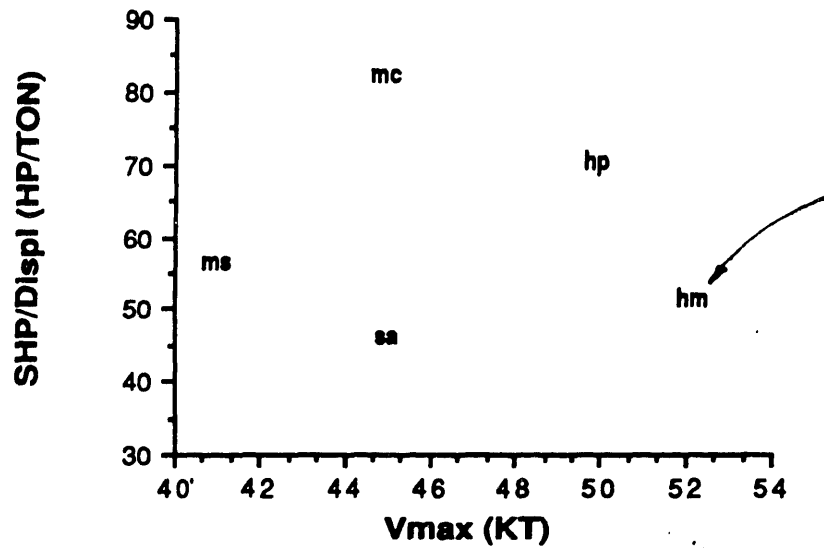
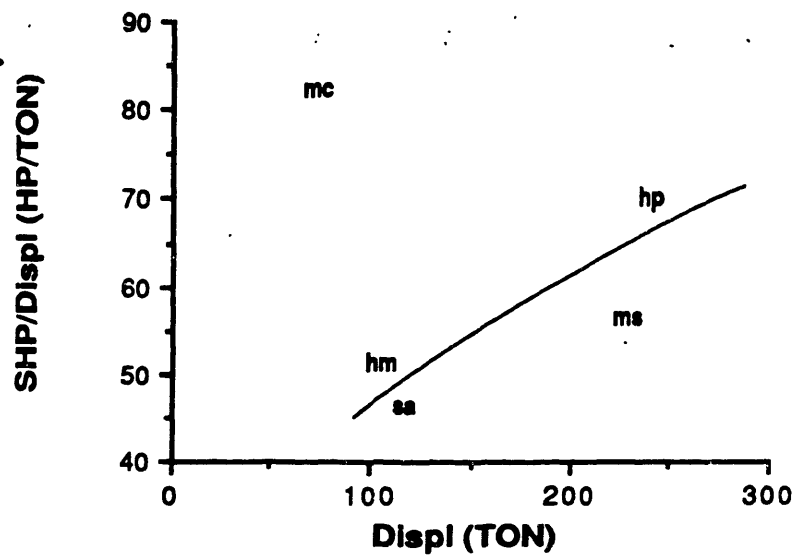
Fig. 5.10 Main prop. ship size ratio vs. max speed**Fig. 5.11 Total HP ship size ratio vs. Displ**

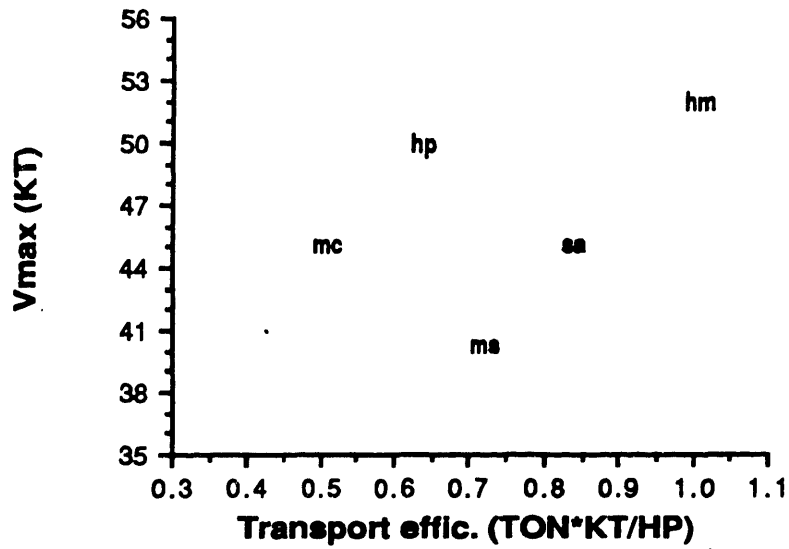
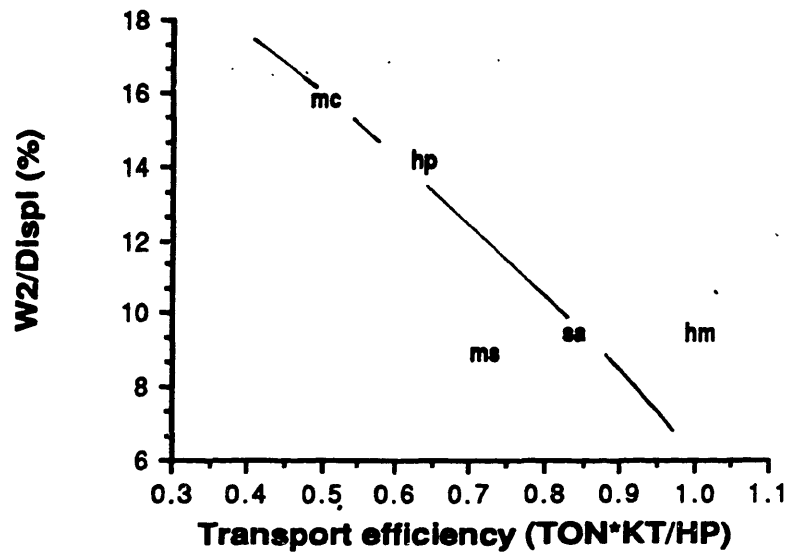
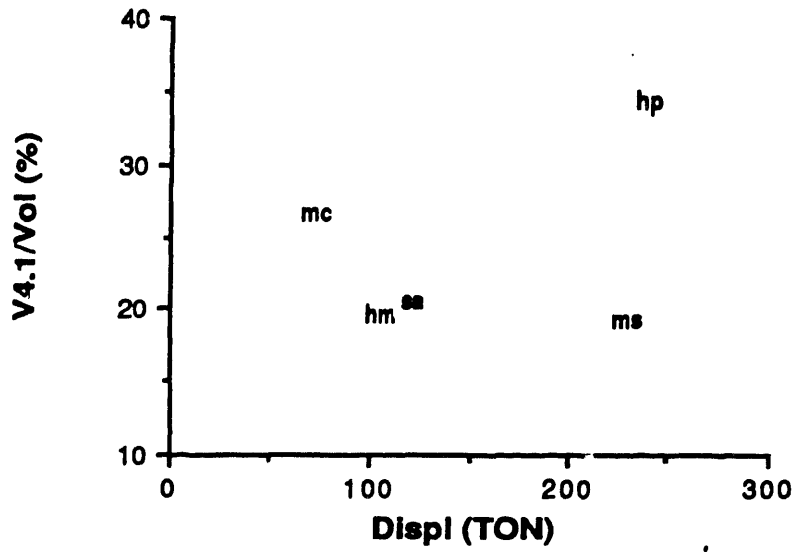
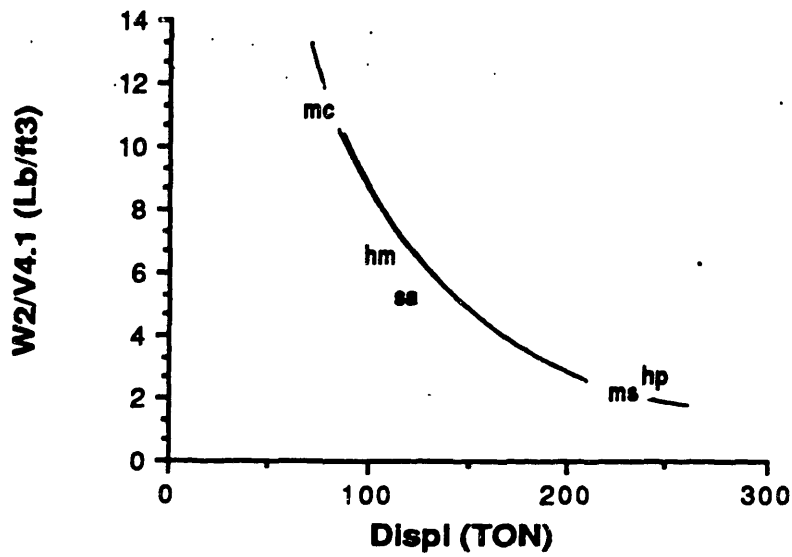
Fig. 5.12 Vmax vs Transport efficiency**Fig. 5.13 Main prop. wt fraction vs transport eff.**

Fig. 5.14 Main propulsion volume fraction vs. Displ.**Fig. 5.15 Main propulsion Density vs. Displ.**

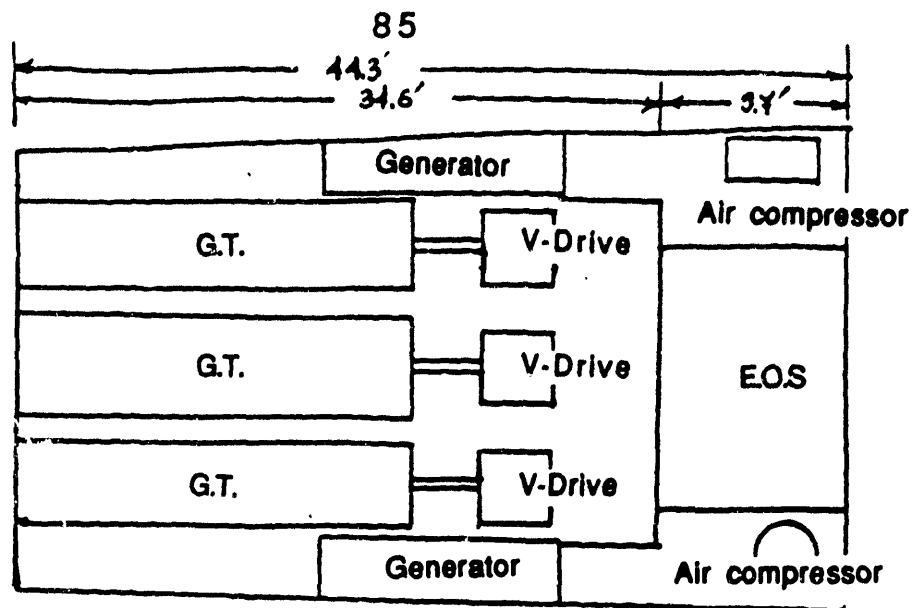


Fig. 5.16 SPICA II Engine Room.

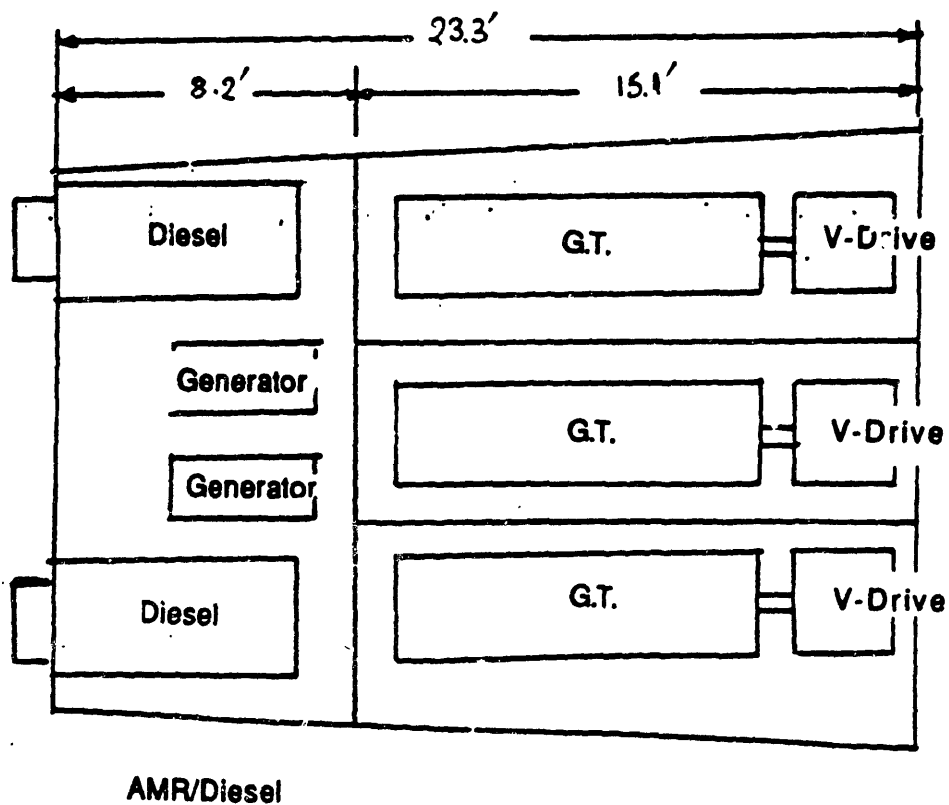


Fig. 5.17 CPIC Engine Room.

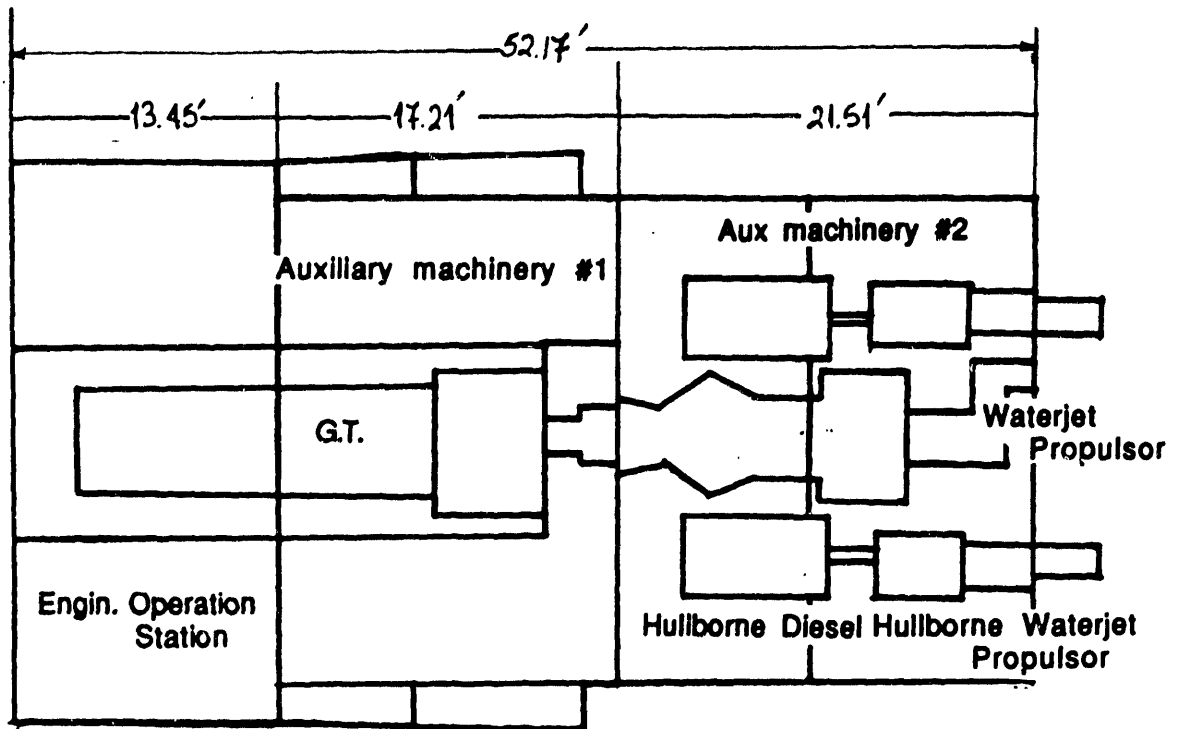


Fig. 5.18 PHM Engine Room.

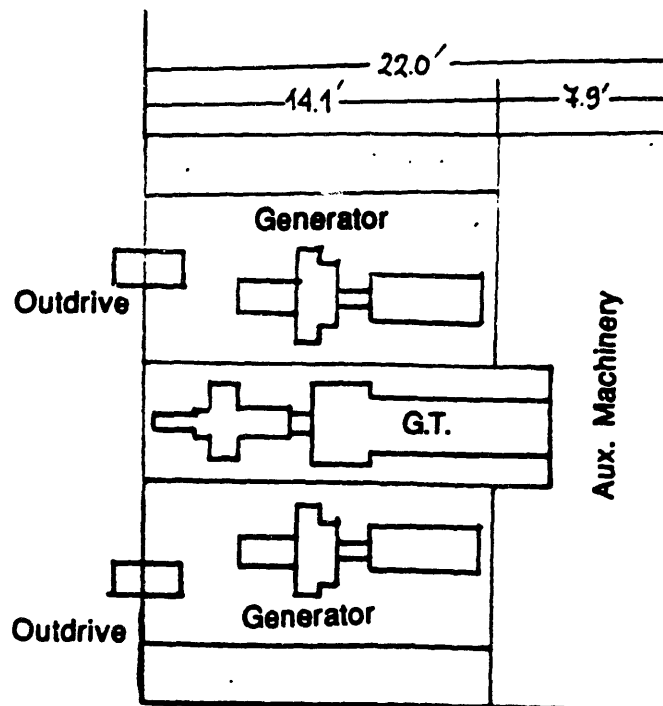


Fig. 5.19 M161 Engine Room.

5.2 Structural design practice

In this chapter structural design practices used for SESs and Hydrofoils is discussed. A comparison with monohull design practices is also provided. Information about monohull's structural design practices can be found at reference 25. The structural materials used to construct each vessel are also presented. A structural weight analysis can be found at the end.

5.2.1 SES structural design practice

The SES is a ship in which the principal payload section is separate from the portion of the hull affected by hydrodynamic loading. SES depends for its functioning on a different means of weight support (air pressure), than a monohull.

SES structural loads are a strong function of the centerbody-to-water clearance. When on cushion, the wetdeck is sufficiently high to reduce the structural bending moments and permit high speed operations at high speed without slamming.

The design method for overall strength used for the monohulls is not applicable for the SESs. For SESs the most dominant load is the off-cushion longitudinal load due to head sea slamming in survival sea states.

The SES vertical accelerations affect the ship structural loads, such as vertical bending moment and shear. In the case of a conventional ship the effect of accelerations is generally to reduce the bending moment since they act counter to the effects of buoyancy. In case

of a SES the main disturbing effects in waves are due to fluctuations in the cushion pressure, and the resulting action of the vertical acceleration (which is effectively equivalent to the pressure variations, since the pressure is the main vertical sustaining force) results in an increase in the structural loads when the acceleration increases. This behavior is opposite to that of a conventional ship.

The different dominant load (compared to the monohull) coupled with the difference in how the SES is supported, leads to increased flexibility for the designer. The shape of the SES can be adjusted to meet mission requirements. The wetdeck height may be adjusted to provide the optimum balance between structural loads (and therefore structural weight), motions, and resistance.

Other than local and point loads, there are two governing loads which the entire structure of the SES must withstand. One is the largest single event load over the ship's lifetime and the second is cumulative fatigue loading.

For SES, the single largest lifetime load usually requires more strength than is demanded by cumulative lifetime fatigue loading. In the cushionborne mode the forces generated by wave impact are the most significant, and also the most difficult to assess. The design pressures exerted on the exposed surface by the wave impact are currently estimated on the basis of experience with seaplane and planing hulls, together with a limited amount on operational data on existing air cushion vehicles.

The hullborne mode of the SES is similar to that of the Catamaran. The ship is subjected to longitudinal bending in head or following seas, spanwise bending on beam seas, and torsion in quartering seas.

Structural design of a SES must take crew safety into account. Crew members must be protected from injury that might result from an emergency condition such as a sudden sharp maneuver or failure of the lift system. Such conditions result in design accelerations of the magnitude of 2 to 4 g's, depending on the direction of the acceleration.

The magnitude of the factor of safety that is used in the structural design is also influenced by the importance of structural member being designed, the consequences of the failure, and the limitation placed on structural weight.

5.2.2 Hydrofoil structural design practice

The structural design of a hydrofoil is similar to that of a monohull, and can be found in reference 54.

The most severe loading considered for the hull plating of a hydrofoil is in the area between keel and chine due to wave impact pressure. The pressure equations that are used do not include any dynamic magnification factor, because the natural frequencies of typical plating panels are much lower than the frequencies of imposed pressure loading pulses.

A certain amount of permanent set for the individual plating panels is used in the hydrofoil ship hull design. This is due to the fact that very few hull plating panels, especially in welded construction, are initially flat. The bottom plating as well as the bottom longitudinal stringers are loaded with the same design impact pressures.

Transverse watertight bulkheads of the hydrofoil are designed for a salt water head to the main deck at midship.

In addition to the monohull design practice, the hull must have the strength to resist wave impact at high speed, as well as distribute the concentrated load at the strut attachment points.

The foil and strut design loads have their origins in the weight and dynamic foilborne lift of the ship, and the distribution of the weight or lift applied to the forward and aft foil systems. Two different kind of loads are considered for the foil and strut structural design. Vertical loads and transverse loads. The basic vertical loads needed for developing the design loads result from the moment balance of the ship when foilborne according to the ratio of dynamic lift on the forward foil. The basic transverse loads required for the development of design loads are calculated in a manner similar to the basic vertical loads, except that an inertia load factor of 0.2g is applied to the ship weight. This lateral acceleration load results from a flat turn, and it is reacted by hydrodynamic side loads on the struts.

Four limit design load conditions must be examined for the structural analysis of the foils: Maximum foil lift, foil emergence, side maneuver and beam sea loads.

5.2.3 Structural Materials

SPICA II is an all Steel vessel, while all the other ships are constructed of Aluminum. CPIC is constructed with Al 5456 Aluminum. The hull and superstructure of the PHM are constructed using welded Al 5456. The hull of M161 is constructed of 5456 Aluminum using 5356 filler rods. The forward deckhouse is of riveted 6061-T6 Aluminum. The aft deckhouse is of 5456 Aluminum. The

structural design of the SES APB34 design was executed, considering Aluminum as the construction material.

Aluminium has a higher maximum allowable deflection than steel, but lower Ultimate Tensile Strength, Yield pressure and elongation. Aluminum is homogeneous, has omnidirectional strength characteristics, is highly corrosion resistant, is easily formed and joined, and can be assembled to hulls without the requirement of expensive tooling.

Al 5086 is an Aluminum alloy of the non-heat-treatable 5000-series. It has very good ductility in the welds and minimal loss in strength when welded. It requires minimum protective coatings, generally only anti-fouling paint for underwater areas, and no coating topside. It does require protection from cavitation and velocity erosion. Al 5086, although slightly inferior in mechanical properties to Al 5456, has less susceptibility in stress corrosion.

Other series of alloys used for the fabrication of the ships studied are the Al 6000-series heat treatable Aluminum alloys. For them, Al 6061-T6 is not suitable for welded construction, since the high mechanical properties that are achieved by heat-treatment are lost during the welding process. However Al-6061-T6 has excellent resistance to the marine environment, and the ability to be extruded into complex thin-gauge web-core shape. It is usually fabricated from integrally extruded shapes and is joined by mechanical fasteners. The fabrication procedure of Al-6061-T6 is further complicated by the problem of obtaining complete watertightness in the fabrication procedure.

The Al 5456 structure of M161 is a longitudinal plate and grillage. Closely spaced longitudinal stiffeners are used. The longitudinal stiffeners consist of tees, result in a minimum weight design.

The basic material chosen for the foils and struts of the PHM was a martensitic, precipitation-hardening corrosion resistance welded 17-4PH steel. Early in the operational life of PHM1, cracks appeared in the skins of the foils, due to material fatigue. Although the levels of the loads used were correct, the frequency of high loads was much higher than what was anticipated. The foils then were redesigned using fatigue criteria, and the next PHMs sail without any operational problem.

In M161 hulls have relatively light plating which consists of plate supported by longitudinal stringers which in turn are supported by more widely spaced transverse frames and bulkheads. The transverse frames and deck beams are supported by system of longitudinal girders. Longitudinal bulkheads have not been included in this design.

5.2.4 Structural weight analysis (Table 5.3)

Overall hull weight fraction is a poor measure of the structural efficiency as it depends on how densely equipment is packaged in the hull. Also differing governing loads make comparison difficult. Thus, in order to make a weight analysis the structural weight fraction is used. The Structural weight fraction (see figure 5.20) could be written as:

TABLE 5.3

STRUCTURAL PARAMETERS

SHIP	CPIC	SPICA II	PHM	M161	APB34
Hull structure					
wt fraction (%)	26.2				
Structural wt		36.6	19.6	19.0	32.3
spec. ratio (Lb/ft ³)	3.6	6.4	2.9	2.7	3.6
Ship density (Lb/ft ³)	13.9	17.6	14.6	14.0	11.2
Hull material	Al	St	Al	Al	Al
Deckhouse material	Al	St	Al	Al	Al

$$W_1 / \Delta = (W_1 / \nabla) \times (\nabla / \Delta)$$

From the above relation we can see that, this fraction is largely driven by the total hull structure specific volume (the inverse of the ship density). The ship specific volume is an indication of the spaciousness, and how much the volume requirements drive the design. The larger the specific volume, the more spacious the design is. It is affected by many variables including length, volume, displacement, hull form, local loading, ship dimension ratios, penetrations, frame spacing and materials. From figures 5.21 and 5.22 we can see that there is a trade-off between ship density and structural weight specific ratio for the four aluminum ships. The denser the ship, the less structural weight is used for a unit of volume.

Figure 5.23 shows the fraction of the different components of structural weight. The exact structural weight fractions for groups 110-180 can be found on table 5.4. APB34 was not included in this analysis as no data could be found or created for the structural components.

The shell of a ship is that part of the watertight envelope that keeps the sea out, and it is the principal strength member of the hull girder. The side shell acts as the web of the girder, and the bottom shell acts as the bottom flange in resisting the primary bending and shear loading. SPICA II, the only steel ship of the study, has very high shell and support weight fractions. This is probably due to the use of more transverse frames, which increase the frame weight significantly. The hull form of SPICA II with a deep Vee forward requires transverse frames for

support. She also has deep floors in the aft part of the bottom, and the fraction of group 110 weight is 61.4%.

The hull structural bulkheads of the ship's structure may be divided into three broad functional groups, namely, "strength", "subdivision", and "tank" bulkheads. CPIC the smallest of the ships, has the most group 120 weight fraction.

The decks of a vessel form platforms that carry normal loadings, such as those due to cargo, machinery and other items on board the ship. They also carry sea loads acting on the topside of the weather deck. Hull deck fraction varies from 13% to 18.3%.

Superstructures are generally configured with some consideration for minimizing aerodynamic drag and protection of the crew during high speed operations without undue construction cost penalties. The very small deckhouse of SPICA II, located aft of amidships, is the main reason of its low deckhouse weight fraction (4.4%).

SPICA II has a very low foundation weight fraction, as her deep floors take much of the foundation fraction load. The hydrofoils' group 150 weight fraction is about 17.5. This is due to a large safety factor for the severe damage that could happen in case of a failure of the foil system while the ship is operating foilborne.

An interesting mission trend appears in figure 5.24, for the different designs of the study. As the speed of the vessels increases, the sum of the structural and propulsion weight fraction decreases constantly, and with a certain slope.

5.2.5 Conclusions

From our experience for the four Aluminum vessels, we can conclude that the use of Aluminum saves weight, at the cost of higher material and manufacturing price.

There is also a trend for lighter machinery and lighter structure, with increasing speed requirement.

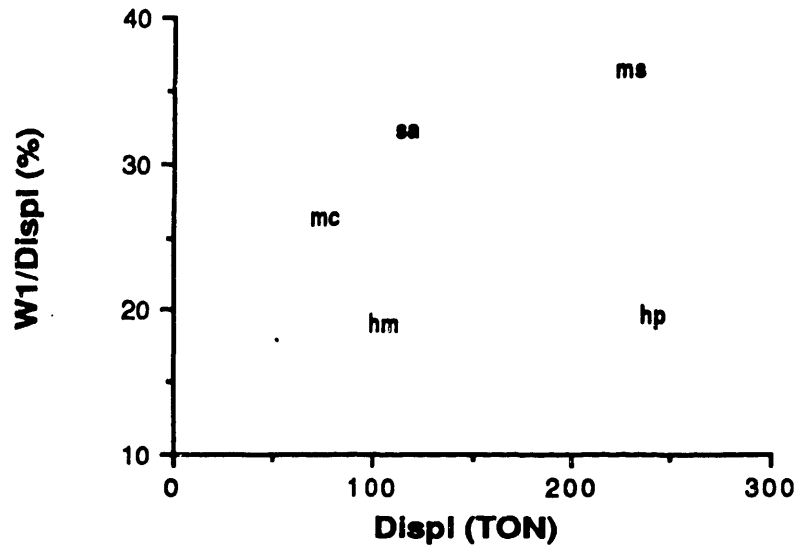
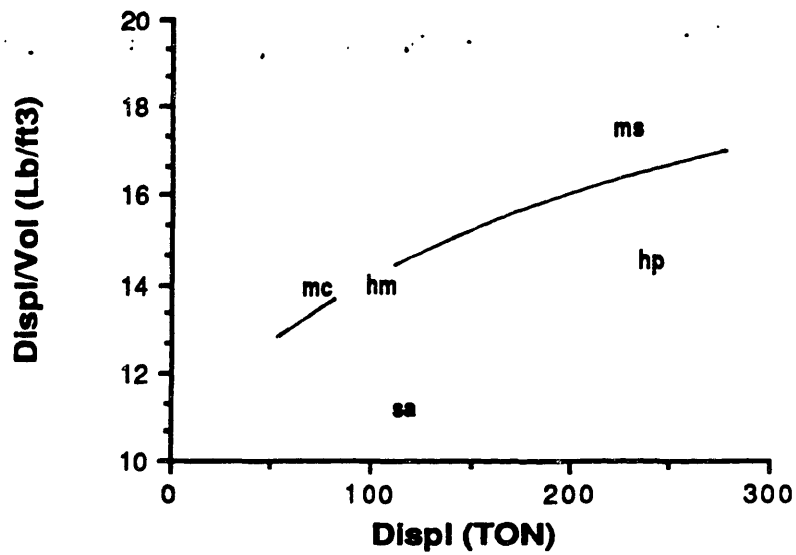
Fig. 5.20 Hull structure wt fraction vs. Displ**Fig. 5.21 Ship density vs. Displ.**

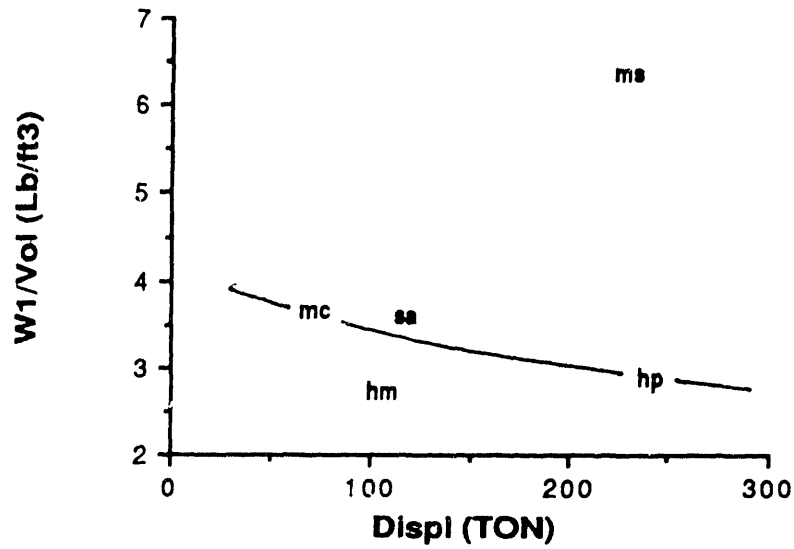
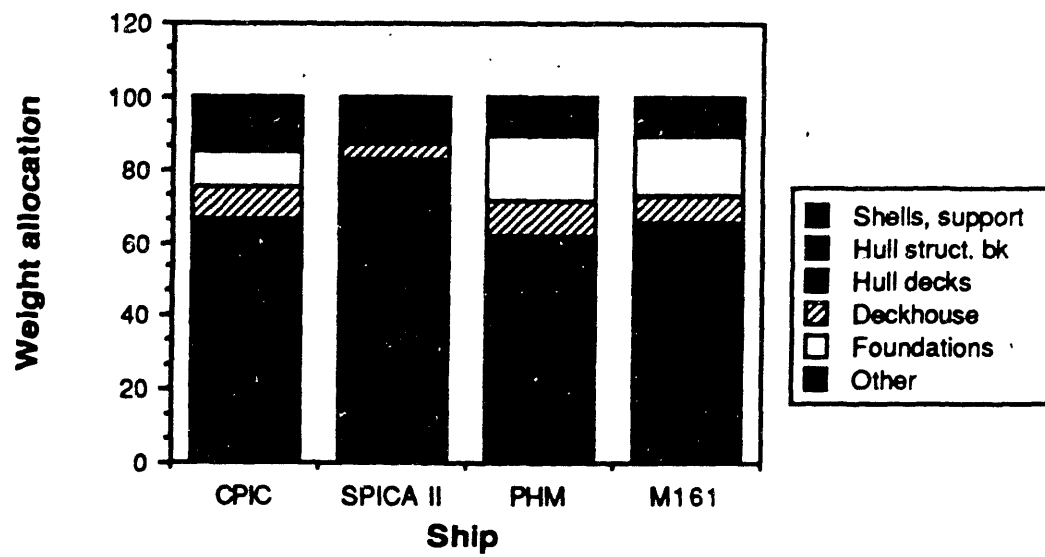
Fig. 5.22 Structural wt spec. ratio vs Displ.**Fig. 5.23 Group 100 weight fraction**

Fig. 5.24 Struct. +Propuls. wt fraction vs. max speed

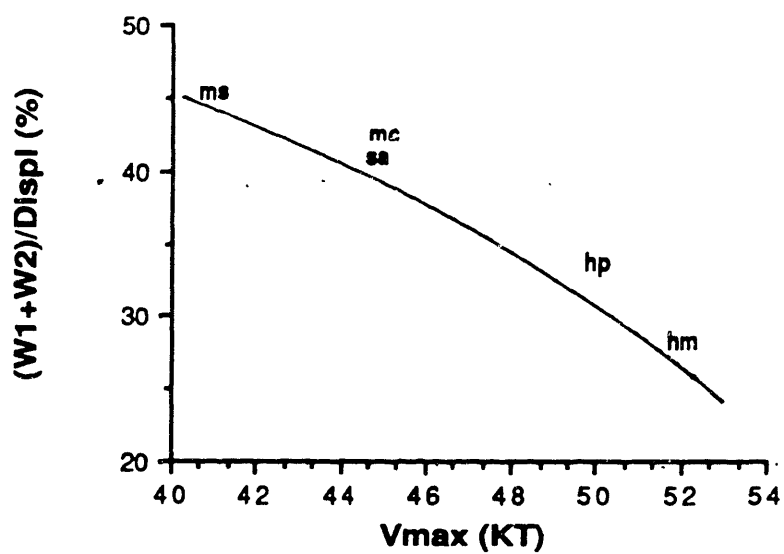


TABLE 5.4

GROUP 100 WEIGHT

SHIP	CPIC	SPICA II	PHM	M161
Shells, supports	38.1	61.4	38.8	43
Hull struct. bkhds	14.0	8.1	4.8	10.3
Hull decks	14.0	13.1	18.3	12.4
Deckhouse	9.0	4.4	10.0	7.7
Foundations	9.6	1.8	17.5	16.0
Other	15.4	11.2	10.6	10.6

5.3 ELECTRICAL POWER

The electrical power weight fraction indicates to what extent the electrical system drives the design. Table 5.5 summarizes all the indices associated with the electrical system of our ships. The electrical power weight ship size trend could be seen in figure 5.25. The W_3/Δ could be written as:

$$W_3/\Delta = (W_3/E) \times (E/W_{PAY}) \times (W_{PAY}/\Delta)$$

From this relation we can see that the weight used for power is impacted by the design standards, the efficiency of the payload in consuming power, and the ability of the ship to carry weaponry and command systems. Instead of the payload weight fraction, the weight fraction of the payload and the auxiliary systems fraction could be used, but the auxiliary systems are considered as a function of the payload for simplicity.

The payload weight fraction varies between 13.3% and 18.6%. This variation is not considered the main driver for the allocation of the electrical weight, as we shall see in the following lines.

The electrical weight specific ratio is a measurement of the electric weight-to-KW efficiency of the plant. A lower ratio indicates that the plant has the capability of delivering more power for a given weight.

The inefficiency of the small generator installation of the CPIC drives its electrical weight specific ratio very high. (See figure 5.26) The two hydrofoils and the SES APB34 have approximately the same W_3/E ratio and for this reason the electrical weight fraction of the M161 and

APB34 should be considered high. Recall that PHM uses a light 400Hz distribution system. Likewise, M161 and APB34 are designed with most modern electronic, and distribution systems which require less electrical plant weight per KW.

M161 has the most efficient payload, as the smallest amount of power is required in order to "feed" its payload. Here we can see a direct link between the Electrical weight fraction and the Electrical power payload size ratio, as can be seen from figure 5.27. The more efficient the payload, the less fraction of the ship's weight is used for its electrical system.

Observing figure 5.28 we can see the size trend of the electrical power ship size ratio. As the ships become larger the less power per displacement is needed for the ships needs. From this rule CPIC is excluded, due to the inefficiency of its small generator installation.

TABLE 5.5

ELECTRICAL POWER

SHIP	CPIC	SPICA II	PHM	M161	APB34
Generators	2x30	2x120	2x200	2x200	2X200
Prime Mover	Diesel	GT	GT	GT	GT
Electrical					
wt fraction (%)	6.6	2.9	4.0	7.2	5.7
Electrical wt					
spec. ratio (Lb/KW)	178.8	62.5	41.4	41.8	37.5
Electrical power					
ship size ratio					
(KW/Ton)	0.83	1.05	1.66	3.80	3.40
Electrical Power					
Payload size ratio					
(KW/Ton)	5.1	7.3	12.5	21.1	18.2
Payload					
wt fraction (%)	16.2	14.4	13.3	18.2	18.6

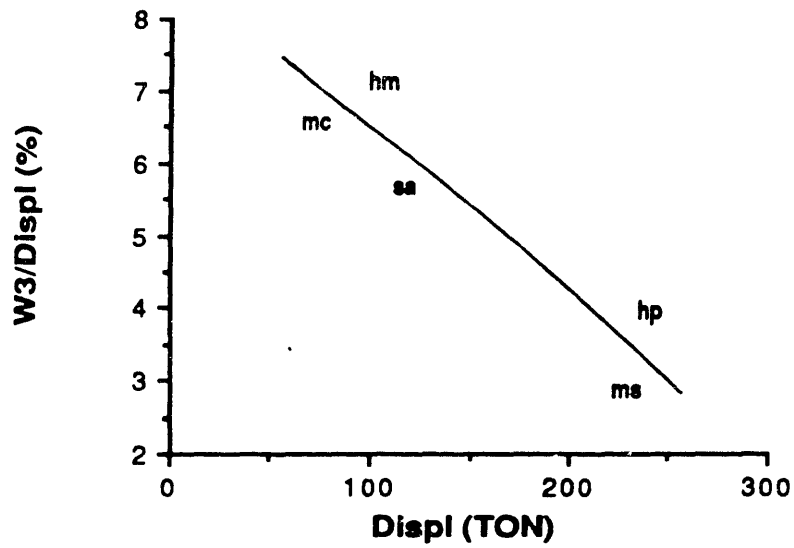
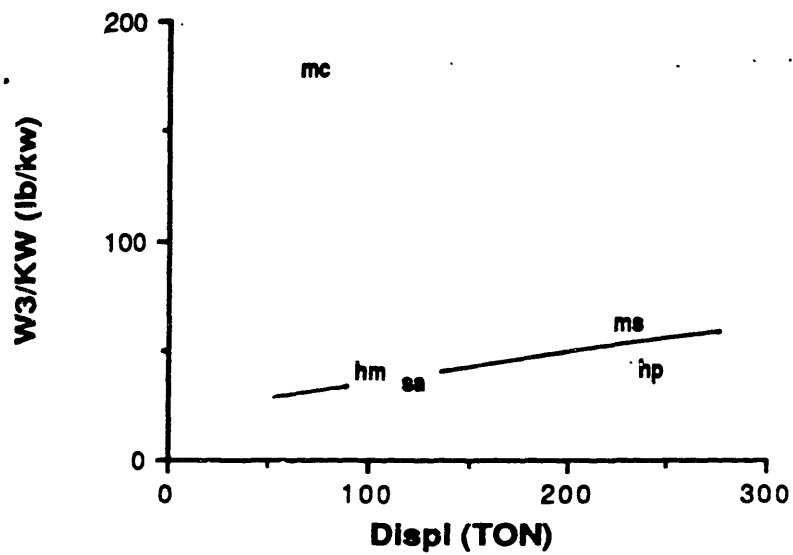
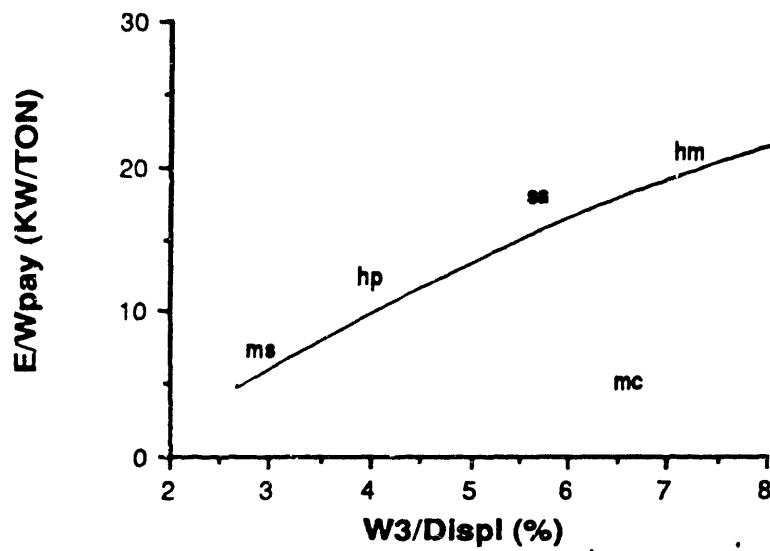
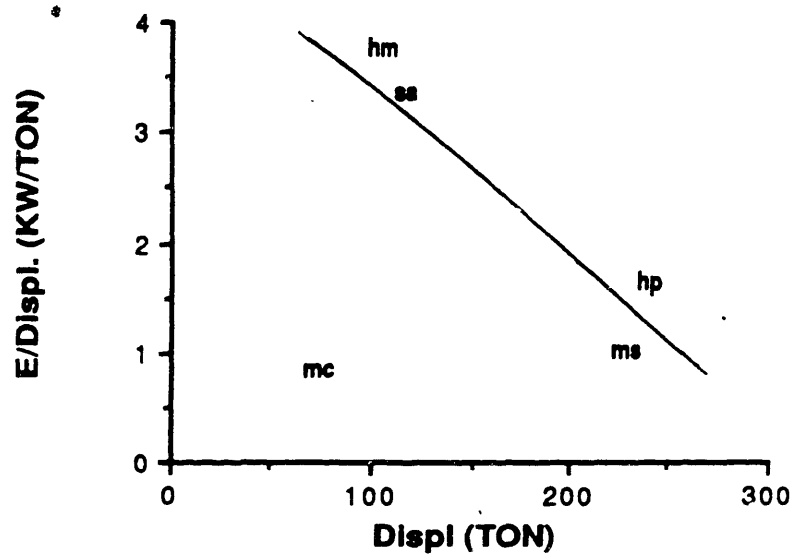
Fig. 5.25 Electrical wt fraction vs. Displ.**Fig. 5.26 Electrical wt spec ratio vs. Displ.**

Fig. 5.27 Payload elect. effic. vs. Electr. wt fraction**Fig. 5.28 Electrical power ship size ratio vs. Displ.**

5.4 PAYLOAD

A ship is designed to carry a certain amount of payload. The more payload weight a ship can carry for a given size, the more effective it can be in its fighting capability, assuming equal quality of weaponry. But in order to achieve better fighting capability there is a need to sacrifice other ship requirements. Payload related indices are presented in table 5.6.

M161 and APB34 seem to be the best of the ships, as far as payload is concerned (see figure 5.29). From these two ships M161 has much smaller payload volume fractions, which means that M161 has denser weapons. CPIC is payload "efficient" as well, although its fighting capability is much smaller compared to the other four ships. From figure 30 we can observe that there is a certain relation between each ship's size, and its armament weight fraction. This size trend is opposite from that of the larger ship and it could be attributed to the lower density of the weapons used in smaller ships in order to save weight but at the same time enhance fighting capability. The armament weight specific ratio follows the same trend. (Figure 31).

With the exception of CPIC and looking in figure 5.32, we can observe the upward trend of the ship's payload fraction vs transport efficiency. M161 is a very capable ship, carrying its weight and a lot of weapons with high speed efficiently. SPICA II comes next. The two U.S. designs lag behind, due to their different design philosophy, and the longer missions in open sea they have to accomplish.

5.4.1 Command and Surveillance (Figure 5.33)

This group includes all sensor and radar systems, including fire control.

M161, with a large radome on the deckhouse, uses the largest portion of its full load weight for command and surveillance systems. Although PHM is designed to operate in more open seas, thus requiring more powerful radar and communications systems, it has less command and surveillance weight fraction. More modern and light electronic systems is a probable explanation of this. Also since sustainability takes weight the payload fraction is reduced.

5.4.2 Ship Operations (Figure 5.34).

Ship operations weight fraction indicates how ship operations drive the design of the ship.

PHM and APB34 the two U.S. designs have a lot of weight and volume dedicated to operations. M161 has the largest proportion of weight and volume for ships operations of the remaining ships. The corresponding sacrifice of the crew amenities, as mentioned above, is a result. There is a certain mission trend for all the ships of the study. As the maximum speed becomes higher, the volume fraction dedicated to mission support is increasing.

TABLE 5.6

SHIP	PAYLOAD			
	CPIC	SPICA II	PHM	M161
				APB34
Payload wt				
fraction (%)	16.2	14.4	13.3	18.2
Payload				18.6
vol. fraction (%)	15.6	17.4	23.3	18.8
Combat system				30.0
density (Lb/ft ³)	15.2	9.7	7.9	16.8
Armament wt				5.1
fraction (%)	9.6	3.6	3.9	15.2
Armament wt				6.3
spec. ratio (Lb/ft ³)	1.34	0.37	0.58	2.05
				0.70

TABLE 5.7
SHIP OPERATIONS

Command+surveillance						
wt fraction (%)	3.3					
Command+surveillance wt						5.1
spec. ratio (Lb/ft ³)	0.63					
Ship operations						0.57
Spec. ratio(Lb/ft ³)	1.5					
Ship operations						3.6
Wt fraction (%)	31.7					
Ship operations						31.6
Vol. fraction (%)	35.0					
						36.7

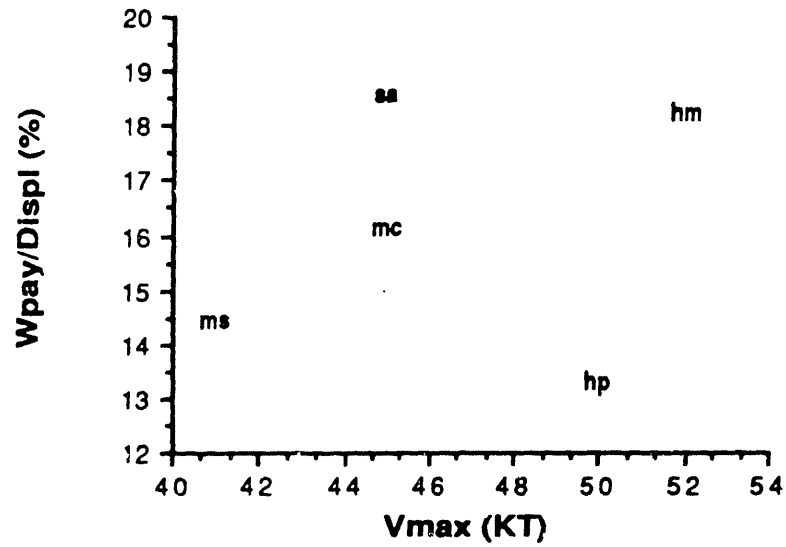
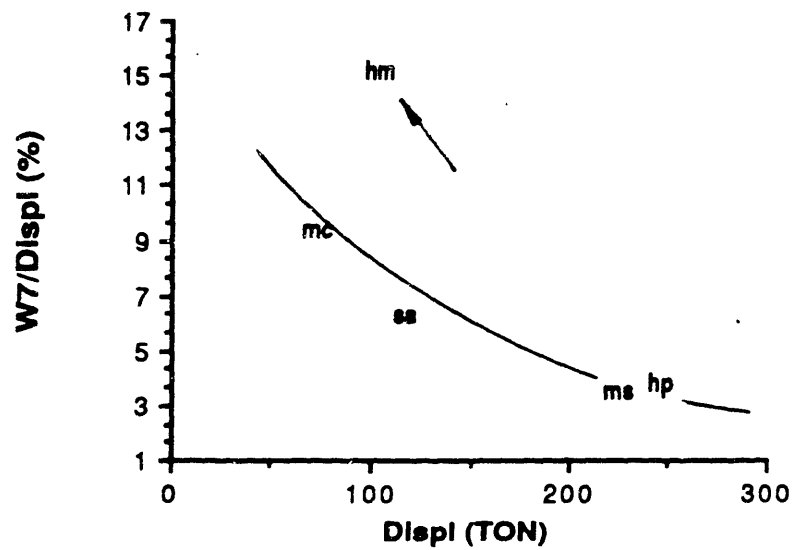
Fig. 5.29 Payload wt fraction vs. max speed**Fig. 5.30 Armament wt fraction vs. Displ.**

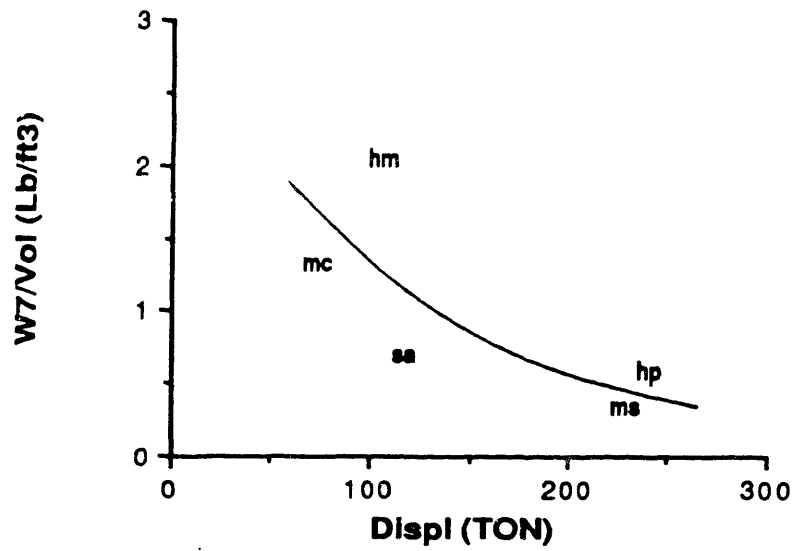
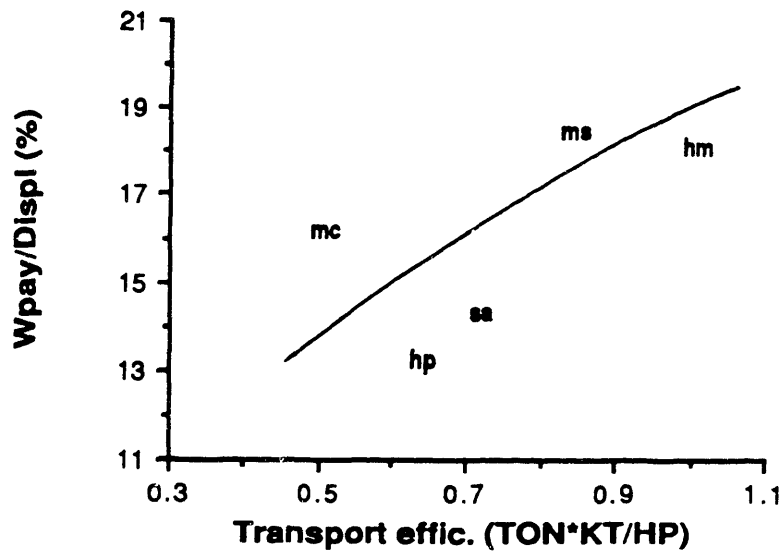
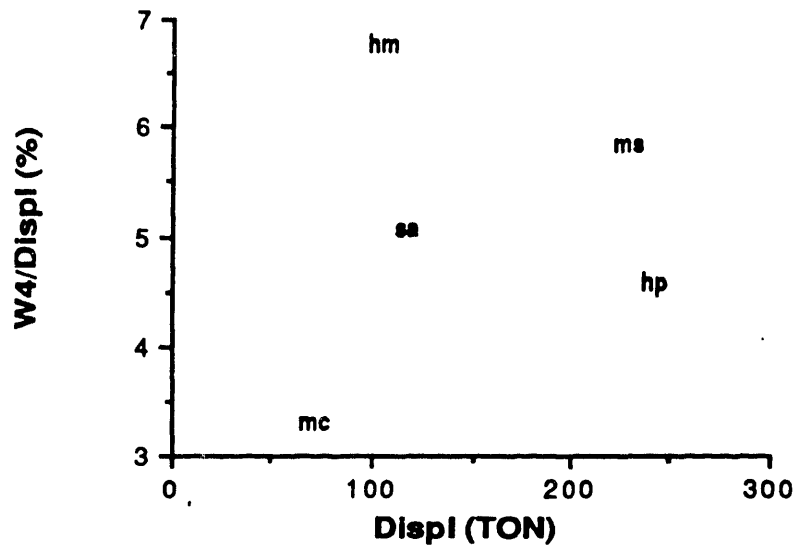
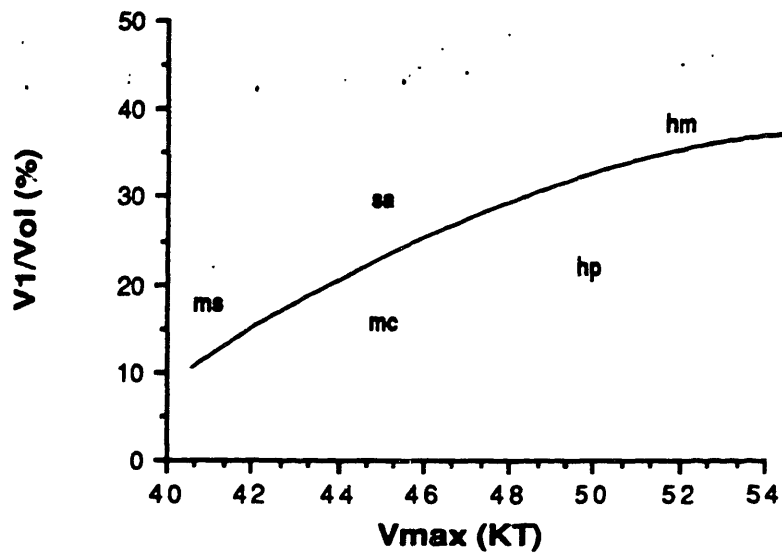
Fig. 5.31 Armament wt spec. ratio vs Displ.**Fig. 5.32 Payload wt fr. vs. Transport effic.**

Fig. 5.33 Command+surveill. wt fraction vs. Displ.**Fig. 5.34 Mission support fraction vs. max speed**

5.5 AUXILIARY SYSTEMS (Table 5.7)

The auxiliary systems weight fraction (figure 5.35) is governed by the auxiliary specific weight (figure 5.36) and ship specific volume. It is a function of the complexity of the auxiliary systems installed. Gas turbine propulsion and increased HVAC requirements for the combat systems and habitability has resulted in an increased W_5 weight fraction in recent decades.

CPIC is an austere ship with no extensive living support. It can sacrifice many auxiliary systems due to its short mission. Therefore its generators are small, habitability low, and $(W_5+W_6)/\Delta$ is low. The auxiliaries volume fraction is average. Its steering mechanism takes a large portion of weight due to use of outdrives for cruising.

SPICA II is about average for most quantities. No special attributes appear to drive this design.

PHM has powerful hydraulic systems to operate the foils and the ship's stabilization mechanisms for both foilborne and hullborne operation. These systems due to their importance are designed with multiple levels of redundancy which increases their weight.

PHM is considered the most "spacious" of all the designs as it is designed with modern U.S. habitability standards, and its long mission length.

The 3,000 psi power needed for the function of the very large hydraulic system of M161 is supplied by two Gas Turbine auxiliary power units. These systems drive the

auxiliary systems weight fraction of M161 up, but not to the levels of PHM, since PHM is a very austere ship.

APB34's auxiliary systems fraction is larger from that of the monohulls, primarily because of the weight of the lift fans, and their driving mechanisms.

The auxiliary systems volume fraction, excluding the foils' operating system, of the hydrofoils is less than that of the other ships. (See figure 5.37). This could be attributed to the much smaller payload weight fraction of PHM which requires less air-conditioning weight fraction, and no steering units, as steering is provided by the foils.

5.6 OUTFIT AND FURNISHINGS

Since most of the outfitting and furnishings weight group relates to human support, it is affected by the crew size and the type of habitability installed in the design.

PHM and APB34 reflect the U.S. design practice with the trend to improve habitability. They have a high W_6 group weight fraction. SPICA II the highest of all the ships, due to the high number of crew. The lowest figure can be seen in M161 due to austerity. So with the exception of M161 there seems to be a size trend for the outfit and furnishings weight fraction (See figure 5.38), as usually more personnel is needed to drive a larger naval ship.

Concluding this section, and looking at figure 5.39 the trade-off between Auxiliaries and outfit and furnishings versus payload and fuel weight fractions, could be

observed. Sacrifice of auxiliaries and furnishings gives more weight fraction to payload and fuel.

TABLE 5.8

AUXILIARIES

SHIP	CPIC	SPICA II	PHM	M161	APB34
Auxiliary systems					
wt fraction (%)	5.2	8.0	18.7	15.3	12.0
Auxiliary sustems					
spec. ratio (Lb/ft ³)	0.73	1.42	2.77	2.07	1.35
Auxiliaries					
vol. fraction (%)	10.6	12.0	9.0**	9.4**	16.0
Outfitting+furnishings					
wt fraction (%)	5.5	8.9	6.9	3.2	7.0
Outfitting+furnishings					
spec. ratio (Lb/ft ³)	0.77	1.56	1.02	0.43	0.79
Ship density (Lb/ft ³)	13.9	17.6	14.6	14.0	11.21
Elect. Load	2x30	2x120	2x200	2x200	2X200
Personnel vol.					
spec. ratio (ft ³ /M)	228.9	290.6	350.8	299-80.0	136.8

* Hydrofoil lift system included

** Hydrofoils not included

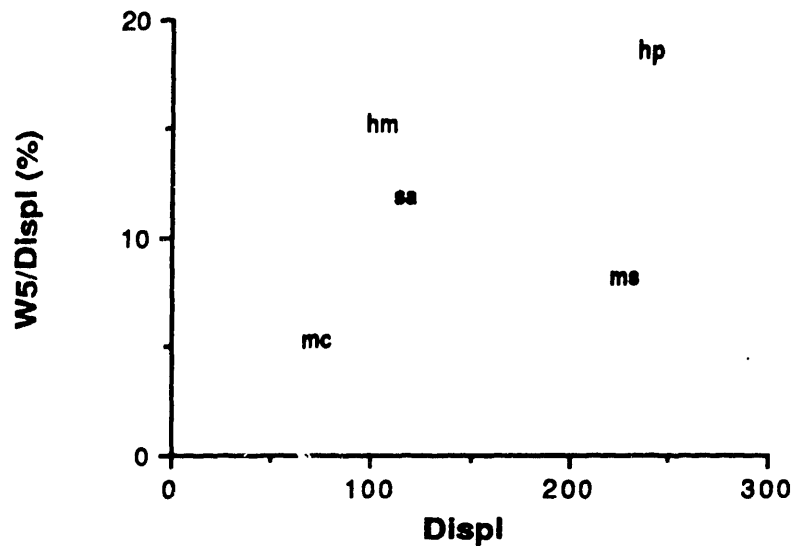
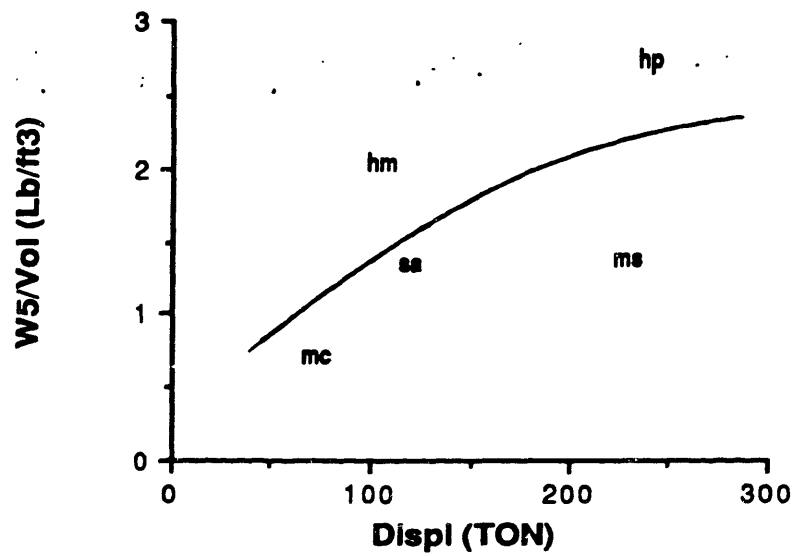
Fig. 5.35 Auxiliary systems wt fraction vs. Displ**Fig. 5.36 Auxiliary systems spec. ratio vs. Displ**

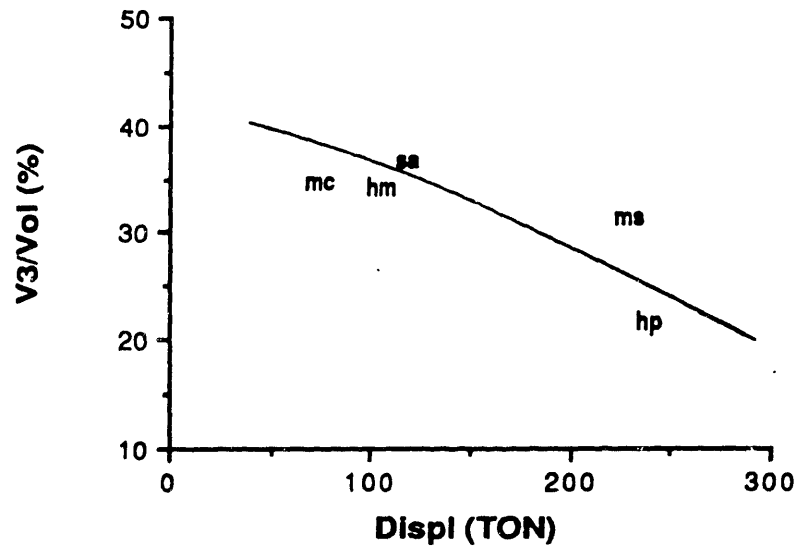
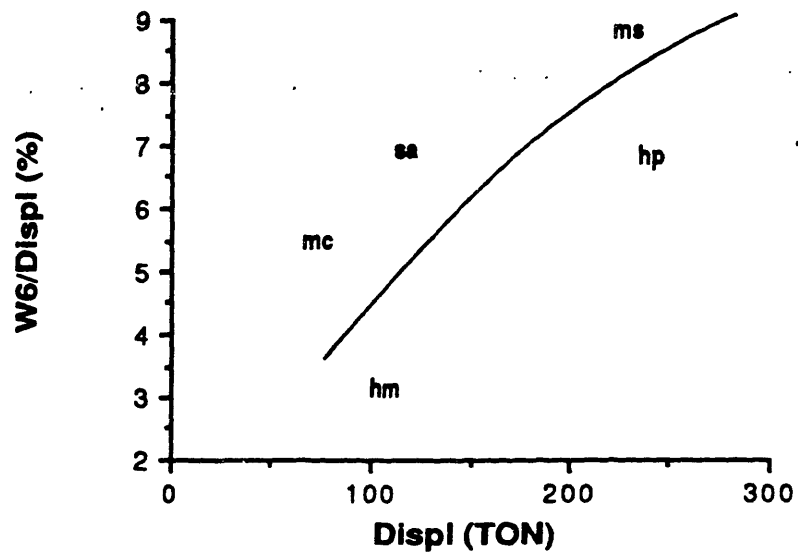
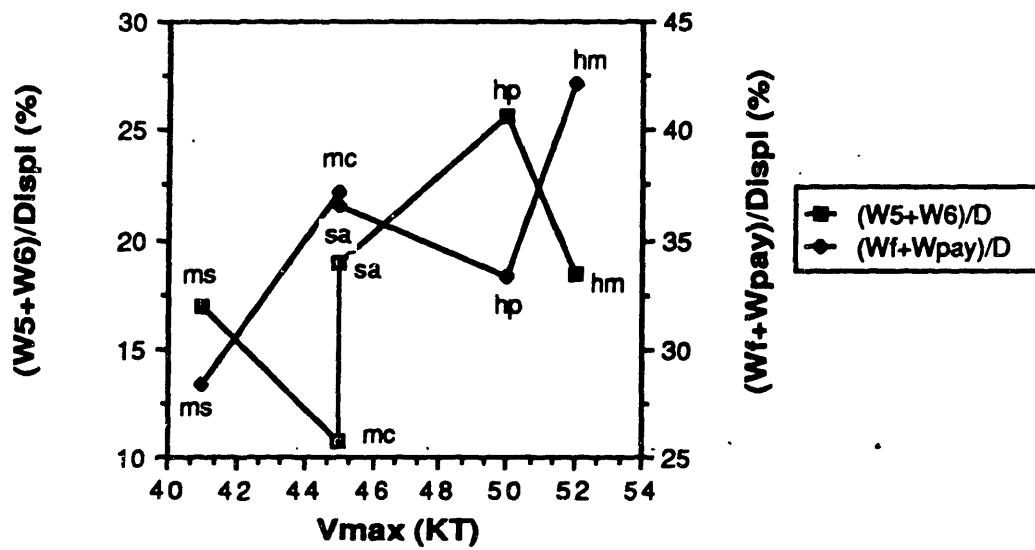
Fig. 5.37 Ship support volume fraction vs. Displ.**Fig. 5.38 Outfit.+Furnish. wt fraction vs Displ.**

Fig. 5.39 Payload vs. Aux. and Outfit trade-off

5.7 PERSONNEL

The design indices showing how personnel considerations affect the design are shown in table 5.8. The number of accommodations impacts the ship by requiring space, weight and energy. The amount of crew carried aboard a ship depends firstly upon the mission of the ship as well as the mission length, and payload. A secondary consideration is the amount of automatic control on board, the efficiency of the personnel, and each navy's standards on personnel education, and philosophy on equipment maintenance and repair. After the crew size is selected, national preference has a large impact on space and weight dedicated to the ship's crew. Other navies design their ships with an "austere" classification regarding volume dedicated to personnel, other with "standard" and others with "plush". So the lower the total manning ship size ratio the more efficient the design from a manning perspective.

PHM and SPICA II are the two ships that can stay on mission longer than the other ships, which with the exception of CPIC, can be considered as "day boats". SPICA II has a difference of 40% of manning ship size ratio from PHM a vessel of the same displacement, probably because of the different kinds of weaponry systems SPICA II carries. There seems to be a economy of scale concerning the crew a vessel can carry. This economy of scale is demonstrated in figure 5.40.

The personnel weight fraction is larger in the ships with longer missions as expected.

The personnel volume specific ratio (figure 5.41) varies from 136.8 (APB34) to 350.8 (PHM). PHM is the roomiest ship due to the U.S. habitability standards, as well as the modern systems and longer mission which needs sustainability. This means more space. Habitability is still reduced in SPICA II and in APB34. The worst habitability could be in M161, when its maximum crew of 15 men are on board. M161 is a great example on how habitability can be a trade-off for performance characteristics when mission duration is short. Looking at figure 5.42 an upward size trend can be seen concerning personnel volume fraction. Thus the bigger ships allocate more of the total volume for crew needs.

5.8 CHAPTER 5 SUMMARY

Chapter 5 identified and explored the differences of the three various designs. Generally we can state that the CODOG plants and the diesel propulsion cost more than the gas turbine propulsion plants. Ship propulsion weight ratio, is a good way to increase speed, but at the penalty of higher cost.

The hydrofoils are most maneuverable and have a better seakeeping capability than the other ships. But in order to achieve this performance their cost, due to expensive control systems becomes high compared to the other ships. APB34 is rated second, as far as seakeeping is concerned, but its cushion pressure control systems need improvement.

Waterjets are less efficient than the propellers, but at the same time noiseless compared to them.

The 400 Hz electrical distribution system of PHM is lighter than the 60 Hz of all the other ships.

Aluminum saves weight, but increases building cost.

Finally in order to save weight for propulsion fuel (increase range), and in order to save weight and space for the payload, different trade-offs are made by the different designers, depending on the country for which the ship has been built, its designed mission, and the amount of time of its exposure at sea.

The attributes and limitations of each ship are presented in chapter 7.

TABLE 5.9

PERSONNEL

SHIP	CPIC	SPICA II	PHM	M161	APB34
Crew	1/2/8	8/6/18	23	3-15	5/4/15
Stores (Days)	2.5	n/a	5	1	1
Manning-Ship					
size ratio (M/Ton)	0.15	0.14	0.10	0.3-0.14	0.20
Personnel Wt					
Fraction (%)	1.8	1.9	1.3	0.7	1.2
Personnel Vol.					
Fraction (%)	22.6	31.9	22.1	7.2	13.3
Personnel Vol.					
Spec. ratio (ft ³ /M)	228.9	290.6	350.8	299-80	136.8

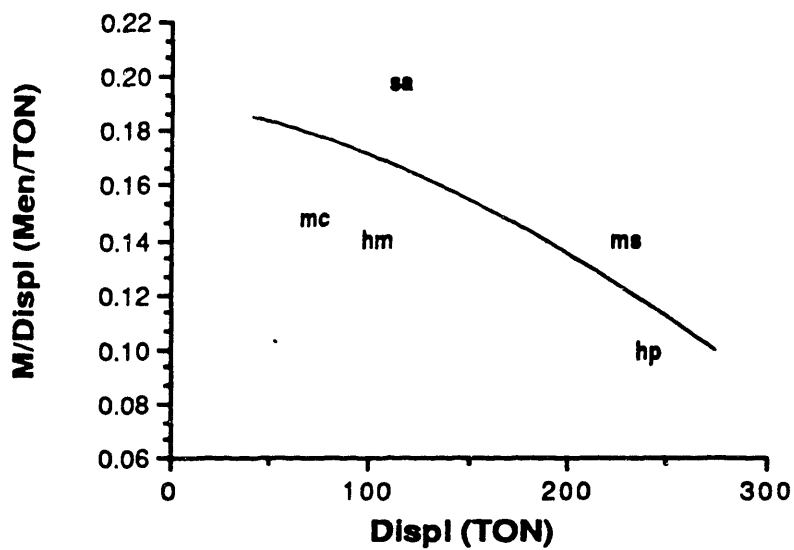
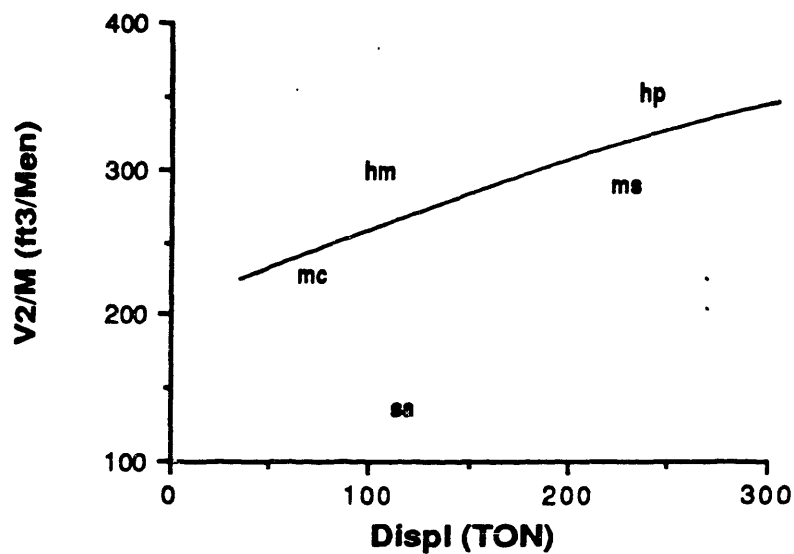
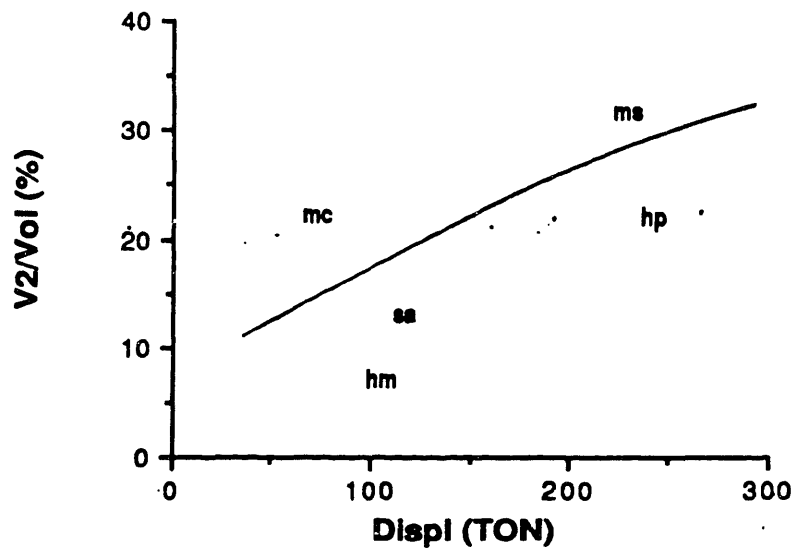
Fig. 5.40 Manning-Ship size ratio vs. Displ.**Fig. 5.41 Personnel volume spec. ratio vs. Displ.**

Fig. 5.42 Personnel Volume fraction vs. Displ

CHAPTER 6

PRODUCIBILITY

One of the chronic problems with military vessels has been a lack of large production quantities to lower capital investment per ship and to permit selection of production methods which could achieve reduced unit costs. During the recent years, there has been more willingness of contractors and vendors to commit to approaches enabling reduced unit costs based on quantity production.

In this chapter, the producibility concepts used in the construction of SESs and hydrofoils will be discussed. The construction methods of SESs and hydrofoils are becoming more and more efficient, as they borrow many producibility concepts from the well-experienced aerospace industry. Producibility for monohull small craft is documented in reference 28.

6.1 Conventional hull and SES producibility

One of the producibility concepts that is incorporated in the construction of conventional Aluminum hulls is the inverted construction. In this way, transverse and longitudinal framing can be set up and shell plating can be wrapped around the hull unobstructed by supporting structure. Gravity is helping with the plating job, external shell seams can be welded flat, and there is far less accumulation of derbies inside the hull. The structure is supported by jigs.

Once the hull is welded, either before or after installation of the deck, it can be rolled over to an upright position using either trunnions welded or bolted to the ends of the hull or nylon straps or cables wrapped around it

Producibility of SESs compared with conventional marine vessels has greater similarities than differences.

A producibility concept that could be used in the construction of APB34, in case it will be constructed is the concept of modularity. This concept has already been used in the construction of SES-100A, BH-110 and SES-200 seals. A probable APB34 modular breakdown is shown in figure 6.1.

In general, with modularity lowering total construction cost is achieved, at least in the small ships of our study. Cost is usually lowered because a smaller element may be fabricated more easily and in larger quantities although several different types of elements may be required.

Finally for SESs which have been constructed and are in operational service, producibility has been addressed by setting a goal to make maximum use of conventional standardized marine equipment. In this way producibility is achieved due to the economy of scale created by the broader marine industry.

6.2 Hydrofoil Producibility

After the completion of the PHM 1 and before PHM 3 design was started, a producibility study was performed to determine ways to simplify the ship's design in order to reduce construction time, to reduce overall welding (a

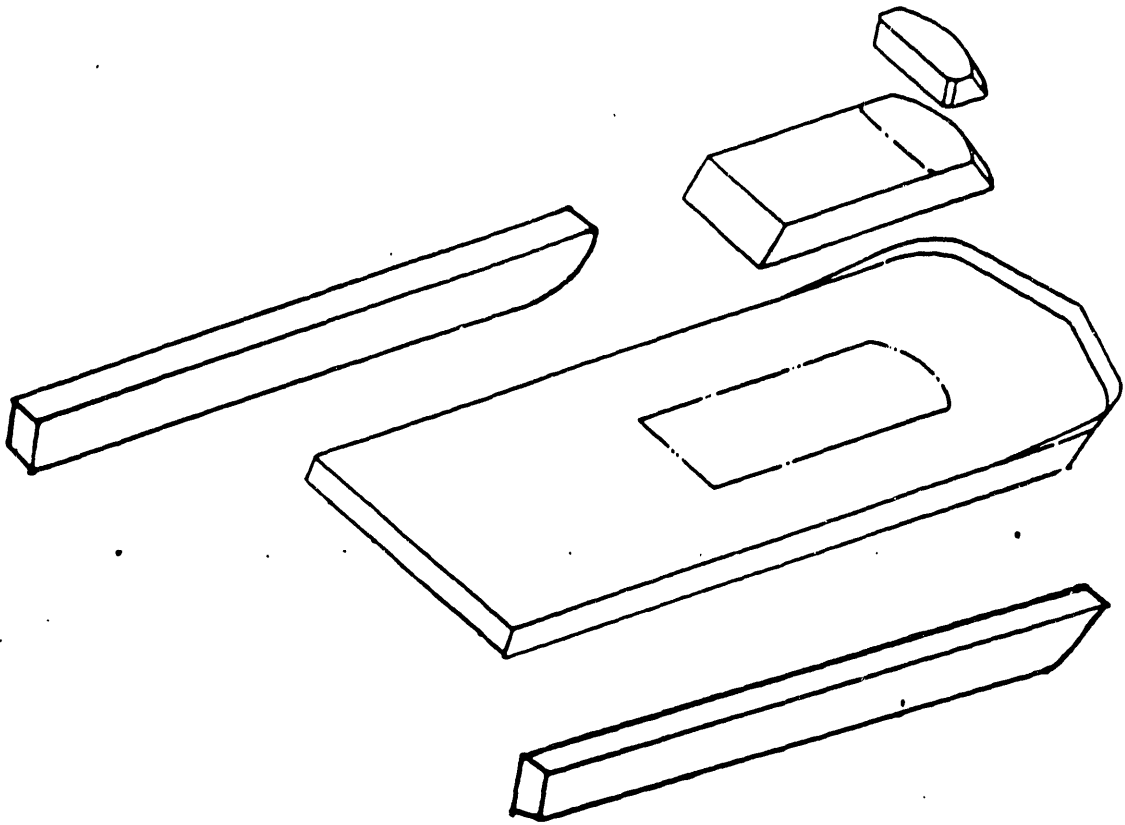


Fig. 6.1 **APB34 Modular breakdown.**

high-cost item), and to improve the end product. This study integrated engineering design with advanced construction technology.

At first, there was a plan for fifteen hydrofoil vessels of the PHM type, five for the U.S. Navy and ten for the German Navy, with a reasonable expectation that additional ships would be procured, thus an economy of scale was expected. The lead ship was constructed using a minimum of tooling. But construction costs had been higher than expected, due at least in part, to welding and distortion problems in manufacturing the hull and foil systems.

The production plan resulting from this study involved modular construction of the hull and foil systems utilizing production tooling for assembly of the modules. The modular assembly schedule is depicted in figure 6.2.

In order to enable the management to maintain high visibility of cost as the work progressed in each station, a revised work breakdown structure was established to collect costs for elements of the assembly sequence (Product-oriented Work Breakdown Structure, PWBS), rather than ship functional elements (Systems-oriented Work Breakdown Structure, SWBS). More information about these construction sequences can be found in reference 56. The plan also incorporated industrial engineering and manufacturing planning techniques normally applied to the airplane production programs permitting efficient utilization of manufacturing personnel from other programs as the work force expanded.

To reduce the amount of welding and the resulting weld distortions, the use of wide-ribbed extruded panels

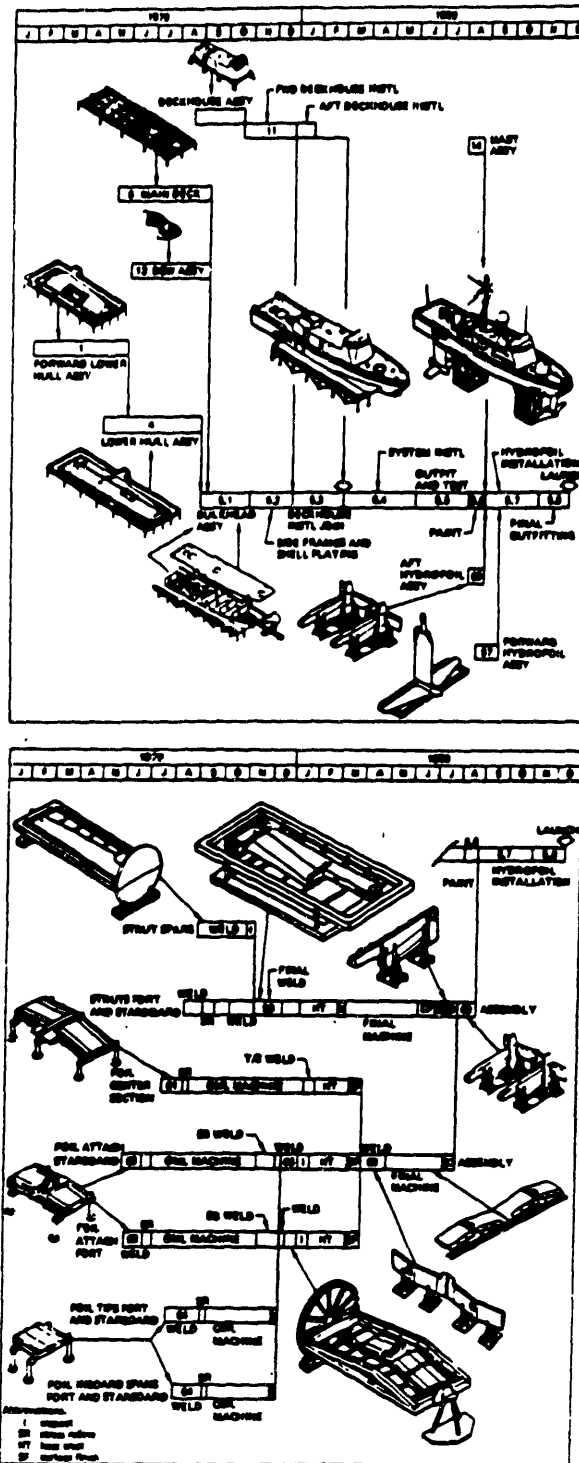


Fig. 6.2 PHM Modular assembly schedule
 (Source: Olling, et al, "PHM design development and production", Jan 83).

wherever practical considerations of fabrication and material usage would permit, was selected.

In the lead ship design, too many parts were used. Also access to welds was difficult. Weld distortion made subsequent fit-up time consuming. The production design resulted from extensive study of lead ship design and construction problems.

The foils and struts of the PHM for the lead ship were constructed in a fairly conventional manner. Difficulty was encountered in maintaining the contours. The underbeads of many of the complex tee welds were not accessible for inspection or grinding.

Very early in the operational life of the lead ship, cracks appeared in the skins of the foils. Inspection indicated that the primary cause of failure was material fatigue. Although the levels of loads used in the design were generally correct, the frequency of high loads was much higher than that previously anticipated. Afterwards, the foils and struts of the production ships were redesigned using fatigue criteria, analytical techniques and design approaches developed for airplane design. In addition to satisfying the requirement for fatigue resistance, the foil and strut redesign incorporated desired producibility improvements such as fewer individual parts, less weld length and increased mechanized welding.

Producibility concepts arose from the production of M161 as well. M161's hulls are of 5456-H111 Aluminum using 5356 filler rods. Extruded planks with integral stiffeners were used for most of the hull structure. This reduced the amount of welding and permitted a large proportion of welding to be done automatically. Seven

transverse bulkheads and 33 transverse stiffeners were used on the design.

6.3 SUMMARY

The producibility concepts discussed in this chapter help the manufacturer and designer produce the ships efficiently and with a lower cost. Ships are designed with small improvements to meet new requirements based on proven conventional and aerospace technology.

The Product Oriented Breakdown Structure (PWBS) gives the opportunity for continuous improvement, and ideas feed-back, permitting efficient utilization of personnel at all levels of manufacturing process.

CHAPTER 7

LESSONS LEARNED

A review of all the previous chapter is presented in chapter 7.

All the vessels of our study are between 70 and 250 tons in displacement. Their primary mission can be summarized to be the attack and destruction of larger surface ships with anti-ship missiles and/or guns. Their secondary missions could include:

(1) Surveillance of coastal areas, especially choke points.

(2) High technology naval presence.

(3) Special operations which include:

Delivery and retrieval of commando-type special force units.

Trailing and shadowing of high interest shipping.

Deception and decoy of hostile forces.

(4) Quasimilitary operations which may include:

Surveillance and protection of fishing and off-shore oil zones.

Antismuggling

Search and rescue.

7.1.1 ATTRIBUTES AND LIMITATIONS OF THE HYDROFOILS (PHM AND M161).

The principal advantages of the hydrofoil ships (M161 and PHM), over the monohull design of our study are:

(1) The ability of the ships which are small by conventional ship standards, to operate efficiently in nearly all ship environments.

(2) The attractive ratio of power to displacement in the 30 to 50 Knot speed range permitting economical operation at these higher speeds. In this speed range, hydrofoils are more efficient than the SESs and the monohulls. Thus for a given ship size and installed power, a higher maximum speed may be obtained.

(3) The exceptional stability of PHM and M161 makes them a superior platform in which to mount surveillance equipment and weapons while maintaining crew comfort and proficiency.

(4) Another naval attribute of PHM and M161 is their radically different pressure and acoustic signatures while foilborne compared with displacement hulls.

These advantages do not come cheaply. Though requiring less power than conventional ships of the same size and speed, power requirements are still high. Therefore, in common with other high performance systems, weight of structures, propulsion and auxiliary systems must be carefully controlled to attain the useful loadweight fractions necessary for effective military ships. To obtain the outstanding rough water behavior demands a foil system with relatively complex strut, foil

and flap structures, automatic control systems and high-power hydraulic actuation systems. Therefore, the cost per ton of M161 and PHM exceeds that of conventional ships. When appropriately designed for military roles which take advantage of the unique operational capabilities the hydrofoil offers, PHM and M161 can cost less when measured in dollars or per unit of applicable performance than CPIC or SPICA II conventional ships for the same role.

The PHM aft foil extends almost 10 feet on either side of the hull. As ship size increases and foils grow relative to the hull and in actual dimension, practical considerations dictate efforts to limit the foil span.

7.1.2 ATTRIBUTES AND LIMITATIONS OF APB34

(1) Since the full displacement sidehulls of APB34 need to be optimized for low-speed hullborne resistance, they are more efficient than most traditional monohulls whose shape must be compromised to be effective at both low and moderate speeds.

(2) The full displacement sidehulls have enough internal volume and deck area to become a useful part of the ship.

(3) APB34 has greater volumetric efficiency than the monohulls or the hydrofoils. This is due to the rectangular shape of the center body which has a block coefficient approaching 1 compared to 0.7 for the other vessels.

(4) APB's deck areas follow the same trends as illustrated for volumes.

(5) The forward draft of APB34 is shallow enough to allow beaching. The low draft allows APB34 to enter harbors and dock at piers too shallow for CPIC, SPICA II or the hydrofoils. The shallow on-cushion draft is less than the running depth of torpedoes making APB34 immune to contact torpedo explosions. The small percentage of the hull in the water significantly reduces the effects of an underwater explosion. The great shock attenuation, due to the small amount of the ship in contact with the water and its shallow draft, means that the design strength built into the APB34 for traditional seakeeping loads is more than adequate to handle these shock loads.

(6) On cushion stability is the most critical stability parameter for APB34. When hullborne, APB34 has the same high initial stability associated with catamarans, and does not require fuel compensating systems or dead weight balance.

(7) The longitudinal and transverse compartmentation, required for structural efficiency allows APB34 to sustain damage in excess of the monohulls, and hydrofoils and remain operable if key subsystems are operable.

(8) When on cushion the wetted surface of the APB34 is drastically reduced which permits high speed operations with reasonable power.

APB34 and SESs generally need improvement in their cushion pressure control systems. An improvement will reduce motion accelerations, thus reduce sea-sickness in high frequencies.

7.1.3 ATTRIBUTES AND LIMITATIONS OF THE MONOHULLS (CPIC AND SPICA II)

The monohull craft of the study and any planing-hull type military vessel have many advantages from a technological view point since:

(1) They do not have serious navigational draft limitations.

(2) They have good inherent roll dumping, due primarily to the use of hard chine. CPIC uses fin stabilizers, which further reduce the roll motions in the displacement speed range, allowing comfortable long-term operation at these speeds.

(4) They can retain a large portion of their calm water operational speed capability in moderate to severe sea conditions.

(5) The construction of their hull can use normal shipyard practice and does not require aircraft-type fabrication techniques. Most of the required structural technology has been used for years, and all the structural design problems have been solved for these ships.

The limitations that follow all these attributes, can be summarized in the following lines.

(1) The lift to drag ratio at high speeds is less compared to hydrofoils and SESs of the same size.

(2) The seakeeping performance in high sea states will never be the same with the seakeeping performance of the hydrofoil craft.

7.2 RECOMMENDATIONS FOR FURTHER STUDY

The number of ships investigated has been limited. A larger data base is required to verify the results of this chapter.

The nonavailability of classified and proprietary data was the main reason for error in this investigation. Some specific areas require more intensive study. Specifically these are seakeeping, and maneuverability. These two issues were discussed only generally in our study.

Another area for extensive study is combat capability assessment. The benefits of various trade-offs, and their impact on the total ship system, should be evaluated and made available to designers.

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APPENDIX A**SHIPS WORK BREAKDOWN STRUCTURE****SWBS****COMPONENT****100****HULL STRUCTURES**

110	Shell+Supports
120	Hull structural bulkheads
130	Hull Decks
140	Hull Platforms
150	Deck House Structure
150	Special Structures
170	Masts, Kingposts
180	Foundations
190	Special purpose systems

200**PROPULSION PLANT**

230	Propulsion Units
240	Transmission+Propulsor
250	Support Systems
260	Supply Fuel. Lube Oil
290	Special Purpose Systems

300**ELECTRICAL**

310	Electrical Plant
320	Power distribution System
330	Lighting System
340	Power generation Support
390	Special Purpose Systems

400**COMMAND+SURVEILLANCE**

410	Command+Control Systems
420	Navigation
430	Interior Communications
440	Exterior Communications
450	Surface Radar
460	Sonar
470	Countermeasures
480	Fire Control Systems
490	Special Purpose Systems

500**AUXILIARY SYSTEMS**

510	Climate Control
520	Sea Water
530	Fresh Water
540	Fuels+Lubricants
550	Air+Gas+Misc. Fluids
560	Ship Control System
570	Underway Replenishment
580	Mechanical Handling
590	Special Purpose Systems

600**OUTFIT+FURNISHINGS**

610	Ship Fittings
620	Hull Compartmentation
630	Preservatives+Coatings
640	Living Spaces
650	Service Spaces
660	Working Spaces
670	Stowage Spaces
690	Special Purpose Systems

700

710
720
750
760
780
790

ARMAMENT

Guns+Ammunition
Missiles+Rockets
Torpedoes
Small arms+Pyrotechnics
Aircraft Related Weapons
Special Purpose Systems

F00

F10
F20
F30
F40
F50
F60
M24

LOADS

Ship Force
Ammunition Rel. Expendables
Stores
Liquids, Petroleum Based
Other Liquids
Cargo
Future Growth Margin

APPENDIX B**SHIPS SPACE CLASSIFICATION SYSTEM****SSCS****GROUP****1****MISSION SUPPORT**

1.1	Command, Communications,
Surveillance	
1.2	Weapons
1.3	Aviation
1.6	Intermediate Maintenance Facilities
1.7	Flag Facilities
1.8	Special Missions
1.9	Small Arms, Pyrotechnics

2**HUMAN SUPPORT**

2.1	Living
2.2	Commissary
2.3	Medical+Dental
2.4	General Services
2.5	Personnel Stores
2.6	CBR Protection
2.7	Lifesaving
2.8	Potable Water
2.9	Pollution Control System

3**SHIP SUPPORT**

3.1	Ship Control System
3.2	Damage Control
3.3	Ship Administration
3.4	Auxiliary Machinery

- 3.5 Electrical
- 3.6 Ship Maintenance
- 3.7 Storerooms, Issue Rooms
- 3.8 Access
- 3.9 Tankage

4**SHIP MOBILITY SYSTEM**

- 4.1 Propulsion System

APPENDIX C**DESIGN INDICES**

<u>Design Indice</u>	<u>Symbol</u>	<u>Units</u>
<u>GROSS CHARACTERISTICS</u>		
Length Overall	L.O.A	ft
Beam	B	ft
Draft	T	ft
Displacement	Δ_{FL}	Tons
Volume	∇	ft ³
Max Speed	V _{Max}	
KT		
Range	R	NM
Boost Engine Horsepower	SHP _B	HP
Total Engine Horsepower	SHP _T	HP
Accommodations	M	Men
Stores	D	Day

SPEED CHARACTERISTICS

Lift/Drag	L/D	(-)
Propulsive Coefficient	EHP/SHP	(-)

Propulsive Efficiency	$(L/D) \times (P.C)$	(-)
Main propulsion wt spec. ratio	W_2/SHP_T	Lb/HP
Main propulsion wt fraction	W_2/Δ	%
Main propulsion ship size ratio	SHP_B/Δ	HP/Ton

DESIGN INTEGRATION PARAMETERS

Main propulsion volume fraction	$\nabla_{4.1}/\nabla$	%
Main propulsion spec. ratio.	$\nabla_{4.1}/SHP_T$	ft ³ /HP
Main propulsion density	$W_2/\nabla_{4.1}$	Lb/ft ³
Total HP ship size ratio	SHP_T/Δ	HP/Ton
Transport efficiency	$\Delta \times \nabla / SHP_T$	Ton*kT/HP

STRUCTURAL PARAMETERS

Hull structure wt fraction	W_1/Δ	%
Structural wt spec. ratio	W_1/∇	Lb/ft ³
Ship density	Δ/∇	Lb/ft ³

ELECTRICAL POWER

Electrical wt fraction	W_3/Δ	%
Electrical wt spec. ratio	W_3/KW	Lb/KW

Electrical power ship size ratio	E/Δ	KW/Ton
Electrical Power	E	KW

PAYLOAD

Payload wt fraction	$(W_4+W_7+W_{AMMO})/\Delta$	%
Payload vol. fraction	∇_1/∇	%
Combat system density	$(W_4+W_7+W_{AMMO})/\nabla_1$	Lb/ft ³
Armament wt fraction	W_7/Δ	%
Armament wt spec. ratio	W_7/∇	Lb/ft ³

SHIP OPERATIONS

Command+surveillance wt fraction	W_4/Δ	%
Command+surveillance wt spec. ratio	W_4/∇	Lb/ft ³
Ship operations spec. ratio	$(W_2+W_3+W_5+.7W_6)/\nabla$	Lb/ft ³
Ship operations wt fraction	$(W_2+W_3+W_5+.7W_6)/\Delta$	%
Ship operations vol. fraction	∇_3/∇	%

AUXILIARIES

Auxiliary systems wt fraction	W_5/Δ	%
Auxiliary sustems spec. ratio	W_5/∇	Lb/ft ³

Auxiliaries vol. fraction	$\nabla_{3.4}/\nabla$	%
Outfitting+furnishings wt fraction	W_6/Δ	%
Outfitting+furnishings spec. ratio	W_6/∇	Lb/ft ³

PERSONNEL**Crew**

Manning-Ship size ratio	M/Δ	M/Ton
Personnel wt fraction	$(F31+640+650)/\Delta$	%
Personnel vol. fraction	∇_2/∇	%
Personnel vol. spec. ratio	∇_2/M	ft ³ / M